Greenleaf (Jas. L.)

[From the American Journal of Science, Vol. II, July, 1896.]

THE HYDROLOGY OF THE MISSISSIPPI.

By James L. Greenleaf, C. E.

presented by the author—

JAMES L. GREENLEAF, C. E.
CONSULTING ENGINEER,
No. 1 BROADWAY.

NEW YORK, July 29, 1896

Mr D. L. Huntington
Depty. Surg. Genl. U. S. Army
Librarian, S. G. O.

Dear Sir

In response to your request of July 25/96 I enclose with pleasure a copy of "Hydrology of the Miss. River"

Very sincerely,
James L. Greenleaf

ART. V.—*The Hydrology of the Mississippi*; by JAMES L. GREENLEAF, C.E.

A RIVER of the size of the Mississippi necessarily has many and important tributaries, with their individual peculiarities of watershed, channel, and variation in flow. Each of these tributaries exerts its proportionate influence upon the stream which is the resultant, and a knowledge of them is therefore essential to a study of the hydrology of the main river. For this reason, sixteen of the branches especially influential in forming the character of the Mississippi, have been selected for a brief discussion.

As a preliminary, it will be well to consider for a moment the point of view from which the engineering profession examines the hydrology of a watershed. Whatever the purpose that the engineer has in working upon a river, be it water power, water supply of towns, irrigation, the training of the current to prevent devastating overflows or to maintain a depth for navigation; in each and all of these problems two fundamental considerations force themselves upon his attention. They are the degree of regularity, and the amount of the volume of flow from the tributary country. Thus, in the south, the Mississippi River Commission and the Levee Boards find the flow volume a vital feature in their efforts to confine the stream in a definite channel. At the north, the Engineer Corps of the United States Army are constructing a system of reservoirs for holding back the freshets and aiding navigation upon the upper river during the season of low flow.

Another item of interest, if not of importance, is the amount of the annual rainfall and its distribution. Although the flow of the streams, or "run off" as it is sometimes called, depends upon the rainfall, yet it bears by no means a direct and simple relation to the latter. The percentage varies with the nature of the country, the climate, and the season of heaviest rainfall, from eighty or ninety down to less than five per cent. Merely

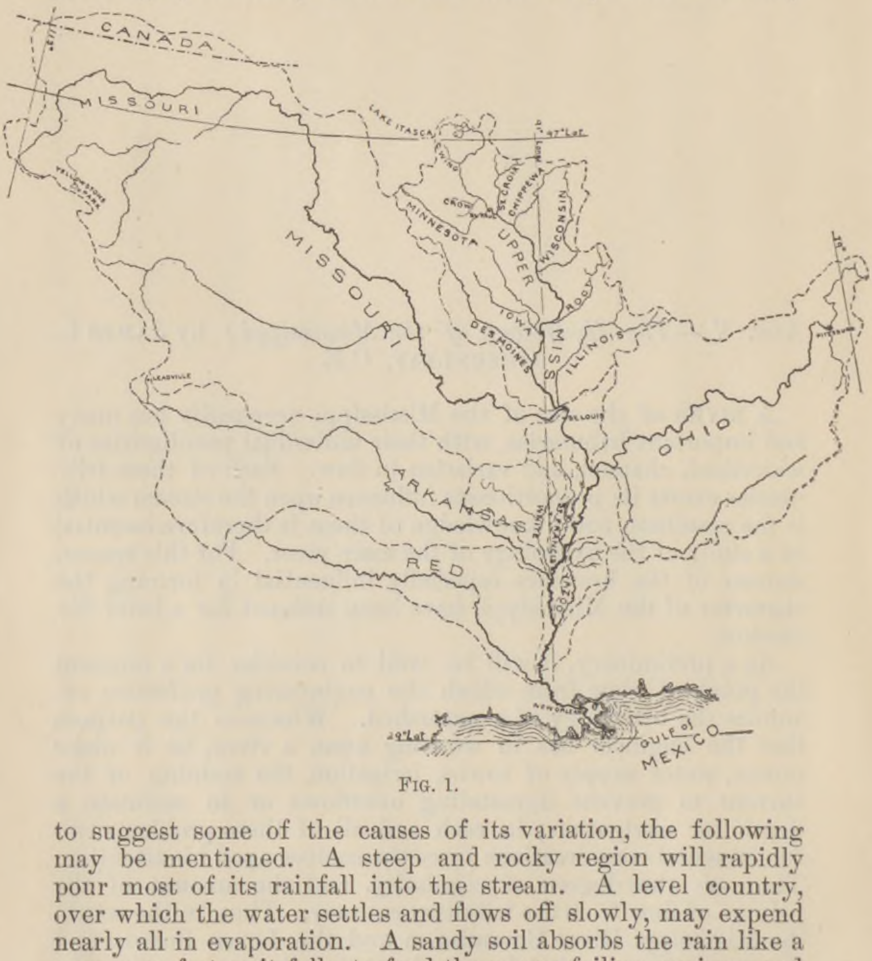


FIG. 1.

to suggest some of the causes of its variation, the following may be mentioned. A steep and rocky region will rapidly pour most of its rainfall into the stream. A level country, over which the water settles and flows off slowly, may expend nearly all in evaporation. A sandy soil absorbs the rain like a sponge as fast as it falls, to feed the never failing springs, and consequently gives a high ratio of flow; or, on the contrary, the water may sink too deep for that, and possibly make its first appearance in some far distant valley belonging to another watershed. A winter rain storm will perhaps all find its way over the frozen ground to the water channels, and a summer shower may be entirely absorbed by the thirsty land and growing vegetation. In fact, the ratio of "run off" to rainfall is so uncertain, that engineers consider volumes of flow deduced merely from records of rainfall of small importance, as compared with a long series of actual gaugings of the stream. But gaugings are seldom available, and hence the percentage that the flow bears to the rainfall is of more than mere scientific interest.

From the foregoing it may be concluded that, in studying the hydrology of a watershed, the engineer considers the area of drainage, the rainfall and its distribution through the seasons, the temperature, the character of the region as influencing the percentage and regularity of flow, and, most valuable of all, actual gaugings of the streams—if he can obtain them.

The basis of this discussion of the Mississippi is a report by the writer upon certain water-powers for the Tenth Census of the United States. The data there given have been amplified to cover the flood and low water as well as the average discharge of the Mississippi and its tributaries, and have been brought up to date by study of the subsequent gaugings conducted by the Corps of Engineers of the United States Army. Acknowledgment is due to this source of information, without which any study of the river would be impossible, and also to the many individual members of the Corps from whom courteous replies have been received to letters of inquiry concerning details. It is believed that the conclusions here offered are an essentially correct statement of the conditions of flow pertaining to the Mississippi watershed. The yearly reports of the United States Corps of Engineers, which are awaited with interest, will either substantiate still further the diagrams here offered, or furnish data for their alteration.

Figure 2 illustrates some of the principal features of the branches selected as especially influencing the Mississippi. The shaded rectangles represent the watersheds in the order of their occurrence from the source to the mouth, and the unshaded rectangles the intermediate areas tributary directly to the main river. The horizontal widths of the rectangles are proportional to the respective drainage areas, and their heights show the yearly average flow in terms of cubic feet per square mile per second. The areas of the rectangles may therefore be said to give a measure of the relative influence of the tributaries upon the average discharge of the main stream.

The diagram exhibits the peculiarities of the tributaries, but fails to furnish an explanation, and that information we must seek for. It will be noticed on the diagram, that the rainfalls, shown by the horizontal lines, increase from the north toward

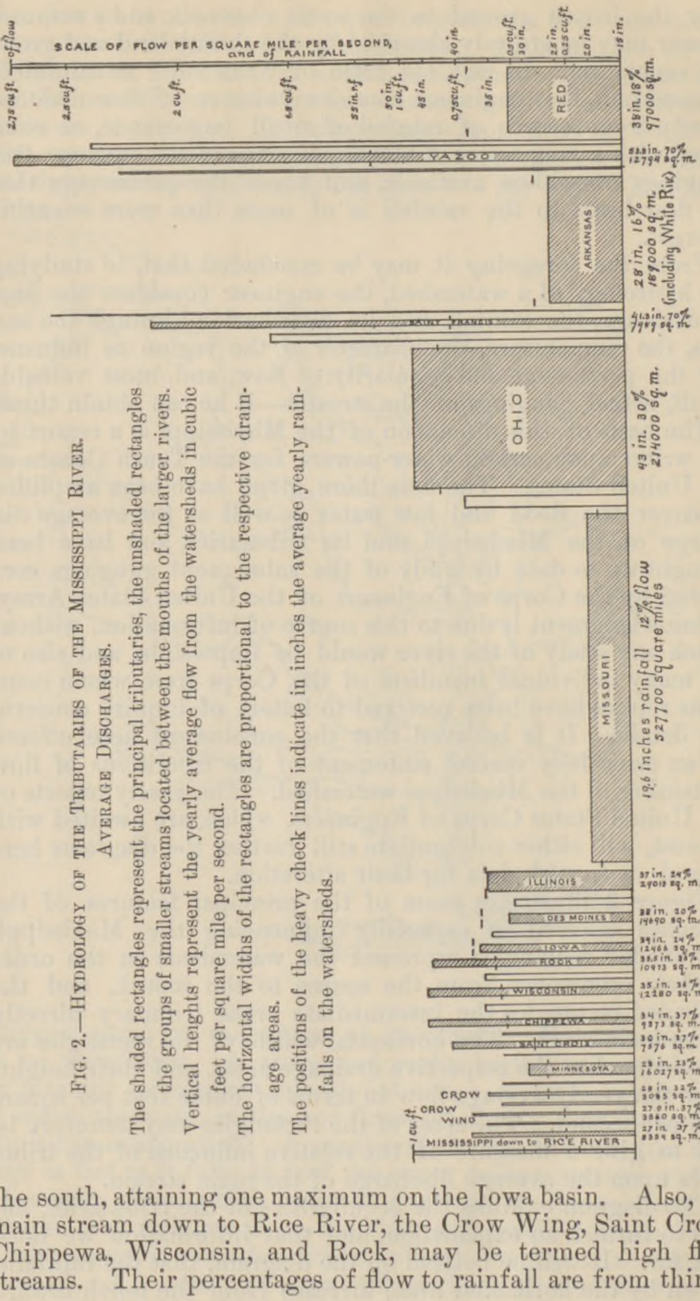


FIG. 2.—HYDROLOGY OF THE TRIBUTARIES OF THE MISSISSIPPI RIVER. AVERAGE DISCHARGES.

The shaded rectangles represent the principal tributaries, the unshaded rectangles the groups of smaller streams located between the mouths of the larger rivers.

Vertical heights represent the yearly average flow from the watersheds in cubic feet per square mile per second.

The horizontal widths of the rectangles are proportional to the respective drainage areas.

The positions of the heavy check lines indicate in inches the average yearly rainfalls on the watersheds.

the south, attaining one maximum on the Iowa basin. Also, the main stream down to Rice River, the Crow Wing, Saint Croix, Chippewa, Wisconsin, and Rock, may be termed high flow streams. Their percentages of flow to rainfall are from thirty-five to thirty-seven, and in this respect they are only equalled by some of the tributaries in the far south. The actual volume of flow, however, is not as great as the figures might lead one to infer, for the annual rainfall is slight, being over a portion of the tributary region only twenty-seven inches in depth. In consequence these streams yield a yearly flow of 0·625 cubic feet per square mile per second, rising to 0·928 cubic feet in the case of the Wisconsin, while the Ohio, for example, although only a thirty per cent stream, gives 0·953 cubic feet of average flow, because of its greater rainfall.

Why is it that the percentage of flow to rainfall for the rivers mentioned, is sufficiently large to raise them into the list of high flow streams in spite of their light rainfall? It may be due, in part, to the spring rainfall being slightly greater relatively to the summer rainfall for the first five hundred miles or so of the Mississippi than for the second, and to the later advance of warm weather at the upper waters causing a delay in evaporation, and in the demands of vegetation. But the principal reason must be sought in the character of the country drained. A sandy soil that absorbs the rain and yields it to the streams with comparatively little loss from evaporation is a feature of a large part of this region. Pine forests that check the dry winds and moisture-searching sun of summer also abound at the sources of the Mississippi, Saint Croix, Chippewa, and Wisconsin.

In contrast to the high flow tributaries is the Minnesota. This river has nearly the drainage area of the Mississippi above where the Minnesota enters it, but in the volume of flow does not approach to the importance of the latter. It is a true "prairie stream," running high at one season, and then dwindling with dry weather, or a cold winter, to almost nothing. Its percentage of average flow to rainfall is only twenty-three, and its average discharge is 0·474 cubic feet per square mile per second. The Iowa and Des Moines likewise flow from an open prairie country and are no better in ratios of flow, yielding only twenty-four and twenty per cent respectively, but in them the increased rainfall shows its effect. Upon these watersheds there is a rainfall of thirty-eight inches annually as against twenty-eight for the Minnesota, and the ten extra inches raise the rectangles considerably above that for the latter river.

The Illinois drains 29,000 square miles to the east of the Mississippi, and is the most important tributary met with thus far in passing down the river. Its rainfall, percentage of flow, and discharge per square mile happen to be almost precisely the same as for the Iowa. The drainage basin also is similar in many respects. The land is level, or gently undulating, but not quite so pronounced a prairie region as the country lying west of the Mississippi. An extensive swamp drains into its head waters from Indiana.

Just below the Illinois is the mouth of the Missouri. Its drainage area is three times as great as that of the entire Mississippi above the junction. It rises in the heart of the Rocky Mountains and flows for nearly three thousand miles through mountain land and prairie. Greatly varying conditions of hydrology prevail within the limits of the watershed, but one fact stands pre-eminent: of all the branches of the Mississippi it makes the poorest record for the area it drains. If its flow was proportionately as great as from the Ohio, its discharge alone would equal the entire volume that passes New Orleans each year. The diagram illustrates the peculiar weakness of the Missouri, due primarily to its low average rainfall, and to the extremely small percentage of flow. Twelve per cent of less than twenty inches rainfall give only 0·178 cubic feet per square mile per second for the average discharge. It is well to remember, however, that these are averages, and that in flood the Missouri is a mighty torrent of muddy water.

A short distance below the mouth of the Missouri, the Ohio enters, with less than half the drainage area of the former, and more than the total yearly discharge. It reaches so far eastward that dwellers on the Atlantic coast look upon its upper waters as neighboring streams. Mountains and woodland cover a large portion of its basin. The rich, undulating farm lands of Ohio, Indiana and Illinois are tributary to it. The large average discharge is not due especially to the percentage of flow, for its thirty per cent is a moderate amount, but to the forty-three inches of annual rainfall. The warm moist air currents which flow from the Gulf region up the Mississippi valley have a decided tendency to the north and east rather than westerly, and this is chiefly the cause of the preponderance of the Ohio over the Missouri. The area of its rectangle in the diagram equals seven-ninths of the combined areas of all the rectangles preceding it, including the Missouri.

The Arkansas is another large river entering from the west, draining 189,000 square miles, and is in many respects a small imitation of the Missouri. Its average ratio of flow to rainfall is only sixteen per cent, and all that tends to raise its standing is the larger average rainfall of twenty-eight inches.*

The Red River is the last important tributary of the Missis-

* The White River, draining 28,000 square miles, has been included with the Arkansas in Figure 2. It is true that they enter the Mississippi together, but strictly speaking they are distinct rivers. It will be noticed that where it is more necessary, as in Figure 4, the Arkansas and White are given separate treatment.

sippi. It flows from the west, bringing the drainage of 97,000 square miles. It maintains not only a slightly better ratio of flow than the Arkansas, but is subject to a decidedly higher rainfall. The former is eighteen per cent, and the latter averages over thirty-eight inches annually. As a result, the Red River yields an average discharge of 0·515 cubic feet per square mile per second. The mouth of the Mississippi is, in a hydrological sense, situated where the Red River enters it, for at this point the Atchafalaya Bayou taps the river and draws off a considerable share of its waters.

It will be noticed that two rivers of marked peculiarities are represented in the diagram. The Saint Francis and the Yazoo are the largest of several streams entering in the vicinity of the Arkansas and the Red, which are comparatively small and do not extend far to the west or east. They are consequently directly in the track of the heavy rainclouds from the Gulf. The rainfall upon their watersheds either sinks rapidly into the sandy soil and thus escapes evaporation, as is the case on a large part of the Yazoo watershed, or else flows quickly into the swamp reservoirs that characterize both the Yazoo and the Saint Francis. Hence the ratio of flow is as high as seventy per cent of the rainfall, and the yearly average flow amounts to 2·130 cubic feet per square mile per second, for the Saint Francis, and to 2·749 cubic feet for the Yazoo.

The second diagram, giving the average flow and rainfall lines of the Mississippi River, follows directly from the diagram of the tributaries. Its special interest lies in the information it affords as to the resultant effect which the branches have upon the main river. The line of flow, "CCC," gives in cubic feet per second the yearly average of total flow at each point from source to mouth. This line will be seen to corroborate a previous statement concerning the large discharge of the Ohio River.

The line "BBB" gives in inches, at any point selected, the yearly precipitation in rain and melted snow, averaged for the entire area tributary to the Mississippi above the point in question. If the point selected is at the mouth of some inflowing river, the line shows the average rainfall above its tributary watershed, and also the effect of including this watershed in the general average.

The line "AAA" is by far the most significant of the three in the study of the hydrology of the Mississippi. It represents for each point from source to mouth the yearly mean flow in cubic feet per square mile per second, averaged for the entire area tributary to the Mississippi above the point in question. If the point selected is at the mouth of some inflowing river, the line shows the average flow from the area above its tributary watershed, and also the effect of including this watershed

HYDROLOGY LINES OF THE MISSISSIPPI RIVER.

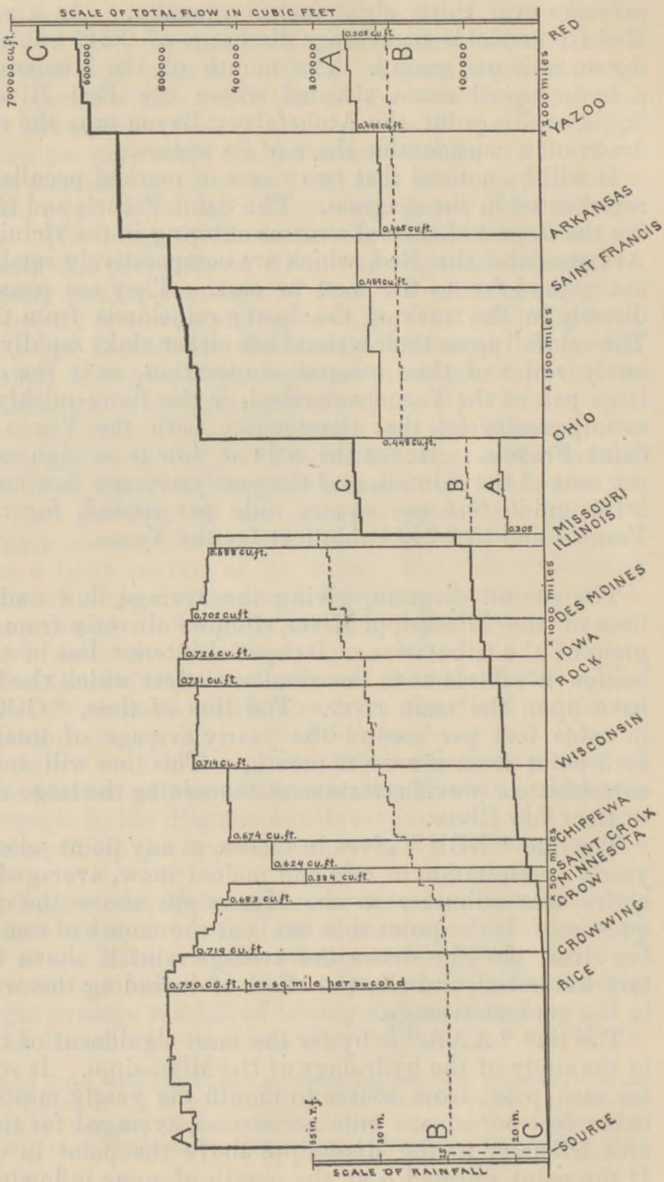


FIG. 3.—The line AAA represents, for any point from source to mouth, the yearly mean flow in cubic feet per square mile per second, averaged for the entire area tributary to the Mississippi above the point in question.
The line BBB gives in inches, at any point selected, they early rainfall averaged for the entire area tributary to the Mississippi above the point in question.
The line CCC gives in cubic feet per second the yearly average of total flow at each point from source to mouth.

in the general average. The line "AAA" is not a simple exponent of totals, as is the line "CCC" of total flow. It is a function of the varying average of rainfall, the varying tributary area as the branch streams are passed, each with its large or small watershed, and the varying percentage of flow to rainfall in force upon these side basins. In the use of this line area enters as a factor of equal importance with volume in the study of the hydrology of the river.

It will be noticed that the effect of any one tributary area upon the line "AAA" is much less marked toward the mouth of the Mississippi than would be the case if its watershed were located at the upper waters. The obvious reason is that it has the weight of all the large areas tributary above it to work against before it can influence the general average. If, for example, the Yazoo and Wisconsin, which have nearly equal drainage areas, were to change places, the latter would cause but slight alteration in the lower end of the line, while the Yazoo, in its new position, would raise the line to a flow of over one cubic foot per second.

It remains to see what general deductions the diagram affords. In the first place, it shows that there is abundant reason for the popular division of the river into the upper and lower Mississippi. The line "CCC" gives the upper river a gradual increase of volume to where it joins the Missouri. At that point begins the lower Mississippi, and the great accretions from the Missouri, and especially the Ohio River, immediately force the line to a higher level. Then the Arkansas and Red Rivers make the rate of increase much greater than for the upper Mississippi. But the line "AAA" exhibits in a decided manner a difference still more fundamental between the upper and the lower divisions of the river. A glance along this line from source to mouth will make apparent the great depression that it undergoes from the Missouri south. The upper river is a high flow stream throughout its length. The lower river belongs just as decidedly with the low flow class.

The depressing effect that the prairie streams have on the Mississippi is marked. Wherever a drop occurs in line "AAA" it is caused by a river upon which prairie influences prevail. The Crow Wing, Crow, Minnesota, Iowa, Des Moines and Illinois exert such effect. The Arkansas causes a decided drop in spite of the large area above that its watershed is averaged with. The Red River alone, of all its class, does not lower the line. This is due in part to its large rainfall, and partly to the line being already well pulled down by the Arkansas to meet it. As for the effect of the Missouri, it is deserving of special notice. A profound drop in line "AAA" occurs at its mouth. If it were not for this, the main river would continue a high flow stream to the Gulf. The extremely small rainfall and percentage of flow of the Missouri, coupled with its half million square miles of drainage area, determine the main river to its mouth. The pronounced high flow character of the Ohio results in the lifting of the line "AAA" at once through forty per cent of the drop occasioned by the Missouri, but even the Ohio, magnificent as it is in drainage area, and with a high rank among the tributaries for its volume of flow, cannot redeem the character of the Mississippi after its debasing union with the Missouri River.

It is interesting to notice that the dual action of the Missouri and Ohio has its imitation toward the north. The low flow Minnesota causes, on a small scale, a drop in the line "AAA" similar to that produced by the Missouri, and below it the Saint Croix and Chippewa are the first of a series of branches culminating in the Rock River, which more than make good the depression.

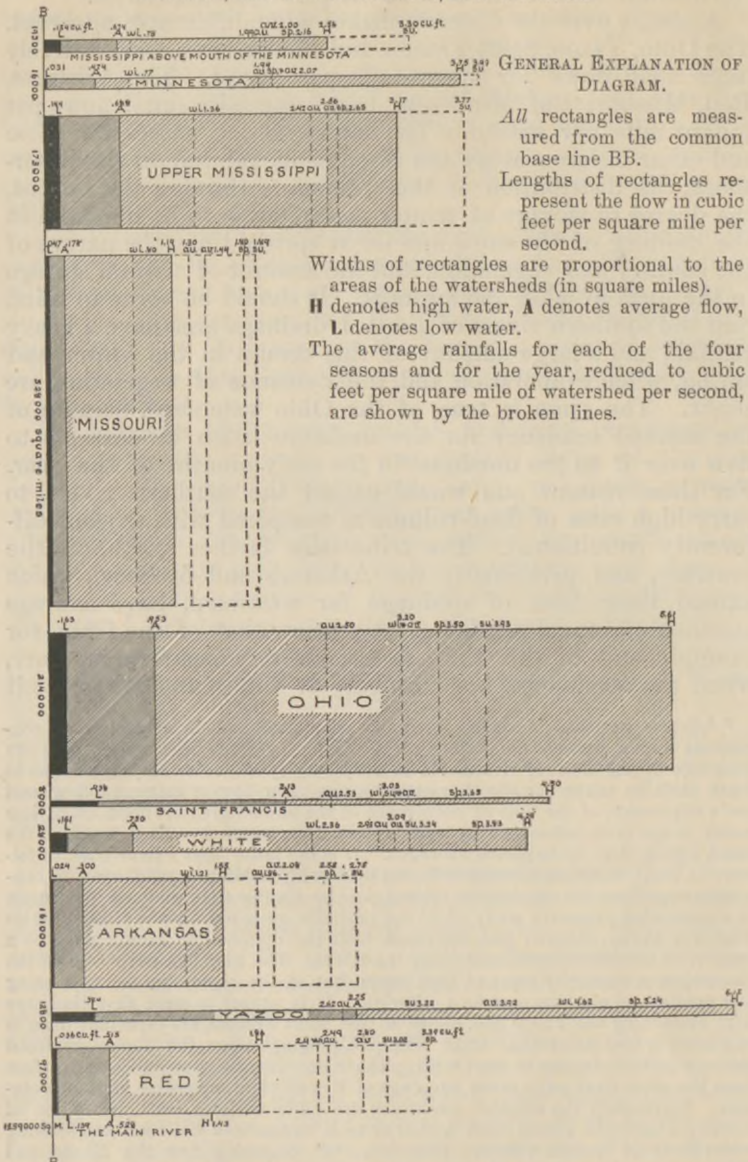
The influence of the heavy rainfall and large percentage of flow in the south is shown by the gradual rising of the line "AAA." The Saint Francis and Yazoo and lesser streams, draining all together only 43,000 square miles, make a perceptible headway in the averages, even against the inertia of all the vast drainage area lying to the north, east and west of them. If their condition of rainfall and flow prevailed over the entire 1,259,000 square miles forming the Mississippi watershed, the average discharge would be fully three million cubic feet per second; more than forty times its actual volume. These figures indicate what the Mississippi, grand river that it is, might be if the trade winds and moist air currents from the Gulf of Mexico did but sweep the semi-arid regions to the northwest, and pour a plenteous rainfall over their vast extent.

Thus far the discussion has been confined to a study of average flow, and is therefore open to the criticism that all averages are liable to, for it states nothing concerning the variations of flow characteristic of the rivers. Indeed, the average flow may even be looked upon as a theoretical quantity, inasmuch as it has no real and tangible existence, except for a few brief periods during the year. No apology need be offered for its presentation, however, for a study of averages is an important aid to the understanding of the actual relation of flow which the rivers bear to one another. Attention will now be given to the variations in the volume of flow of the tributaries of the Mississippi, and the relations which these variations bear to the climatic and topographical features of the watersheds. Figure 4 and the subsequent notes present particulars concerning rainfall, minimum and maximum flows, and the time variations in the amount of flow for each of the principal tributaries.*

A glance over the diagram makes wide differences apparent. The Ohio, Yazoo, Saint Francis and White have comparatively large flood flows per square mile per second. The Arkansas, Red, Missouri and Minnesota have especially small flows per square mile per second. The determinating causes for these and other differences are the amounts of rainfall on the watersheds, the distribution of these amounts through the seasons, the degree of storage of winter precipitation to be liberated in the melting of the snow and ice at spring time, the nature of the country and vegetation, and the amount of natural storage in the form of lakes and swamps. It should be borne in mind that the southern rivers of limited drainage area have a heavy rainfall, and a large amount of this occurs in the winter and spring, when evaporation and the demands of vegetation are slight. The same is true of the Ohio watershed, because of the marked tendency for the moisture laden air-currents to flow over it to the northeast in the early months of the year. For these reasons one would expect the southern rivers to carry high rates of flood-volume as compared with streams differently conditioned. The tributaries farther north, on the contrary, and particularly the Arkansas and Missouri, which extend their lines of drainage far westward, have average amounts of annual rainfall greatly below that of the Ohio, for example, and of this the greatest activity occurs in summer, when the tendencies are strongest to absorb and evaporate it

* Adverse criticism is almost inevitable when one puts in concrete form conclusions from a series of data which are so liable to various interpretations as are gaugings of the flow of rivers. It is very largely a matter of judgment as to what shall be taken for the characteristic minimum flow or maximum flow, and one's impression of the time of occurrence of the annual greatest flood, or of low water, is apt to be influenced by some special case which has fixed itself on the mind, rather than by impartial averages. It is the latter that I have tried to follow. I hope to disarm adverse criticism by frankly holding myself open to conviction regarding the conclusions offered, and by stating that they are the result of a somewhat extensive study of all the available gaugings by the United States Engineer Corps. checked and compared with the opinions so kindly given by a number of the officers stationed along the rivers. The aim has been to give the discharges at decidedly low and high water, but at the same time to avoid using any special and extreme case as a criterion. It is proper to state that discharge data concerning the Yazoo and, above all, the Saint Francis, are especially meagre and more or less uncertain. Capt. Willard's gaugings upon the Yazoo are about the only reliable figures to start with. The Saint Francis is so liable to overflow from the main river as to make gaugings of it well nigh impossible of interpretation. Fortunately the climatic conditions are quite uniform over the region of country concerned, giving some authority to a comparison between neighboring watersheds of limited extent. Therefore, by comparing first the Yazoo and White, giving due value to the proportions of upland and bottom land, and then applying the results to the Saint Francis, and checking by a proper balance between the three rivers, results have been obtained which I believe to fairly represent the truth.

Fig. 4.—Hydrology of the Tributaries of the Mississippi River, High, Average, and Low Discharges, and Rainfall.



General Explanation of Diagram.

All rectangles are measured from the common base line BB.

Lengths of rectangles represent the flow in cubic feet per square mile per second.

Widths of rectangles are proportional to the areas of the watersheds (in square miles).

H denotes high water, **A** denotes average flow, **L** denotes low water.

The average rainfalls for each of the four seasons and for the year, reduced to cubic feet per square mile of watershed per second, are shown by the broken lines.

Notes on the Times of High and Low Water.

Mississippi above the Minnesota. *High.*—Rise begins in early April, due to Spring rains and melting snow—reaches a max. in end of April to May, and often is the max. of the year. Effect of melting ceases, but rains maintain a fair stage. Decided rise in June to July, due to rains—sometimes the highest of the year. Generally a brief Fall freshet.

Low.—The low water of Fall occurs in August to Nov.—usually lowest in end of Sept. to mid. Oct. Lowest water of year in end of Nov. to end of Dec., due largely to freezing of the ground.

Minnesota.—Practically the same in period of rise and fall as the Mississippi above it, but much more fluctuating in amount, because of the comparatively few lakes and swamps, and more open prairie on its watershed.

Upper Mississippi (down to Missouri River). *High.*—Rise begins in Feb., due to rains and melting snow. A good stage maintained well into July. Usually two occasions of especially high water. The smaller may occur any time from latter part of Feb. to end of March, due to rains and melting snow. The greater may occur any time from April to July, due to rains and somewhat to melting snow. There is often a brief Fall freshet.

Low.—The lowest water of the Fall occurs in Aug. to Oct., generally in Oct. The lowest of the year is in Dec, due largely to freezing of the ground.

Missouri. *High.*—The volume of flow increases from early in Feb. on, reaching a max. in April, due to rains and melting snow. Owing to the large differences of elevation on the watershed, melting snow influences the stage of the river until Aug. A fall occurs in May, as the bulk of the snow disappears. Then there is a rise in June to the max. for the year, falling in July and Aug.

Low.—The river runs low in Sept., Oct. and Nov., and in the latter part of Nov. into Dec. occurs a sudden drop to the lowest stage of the year, due to freezing of the ground.

Ohio. *High.*—The river usually begins to rise in the latter part of January and is liable to maintain a fair stage until into July. In latter part of Feb. on, into the latter part of March, occurs the max. rise of the year, due to winter and spring rains and melting snow. Again, in April to middle of May is the height of a secondary rise, due to rains solely. The Fall rains cause an occasional rise in Nov.

Low.—The low water is in August through to Jan., and the lowest is any time from the first of Oct. to the middle of Nov.

Saint Francis. *High.*—The river rises to a good stage in the middle to end of Jan., diminishing through May. The highest stage usually occurs in the latter part of March.

Low.—Low water runs through Sept. to Dec., usually reaching the lowest point in the end of Oct. to the end of Nov.

White. *High.*—There is usually a good stage from Jan. to June, a fall sometimes intervening. The highest water may occur any time between those limits, with the chances in favor of its coming in May.

Low.—Low water occurs from July into Dec., and the lowest stage of the year from Sept. to Nov., especially in Nov.

Arkansas. *High.*—A good stage of water is liable from Jan. to June. A max. occurs in Feb., and again in April or May, and the chances are about even in the long run for either of these being the max. for the year. There is often a brief freshet in the Fall.

Low.—The river falls in July, and, except for Fall freshet, runs low into Dec. Lowest stage of the year is liable from end of Sept. to middle of Nov.

Yazoo. *High.*—There is a good stage of water from Jan. to June or July, culminating usually in April. An irregular and occasional rise occurs any time from Aug. to Dec.

Low.—The river runs low as a rule from July through Dec., reaching a minimum in the latter part of Oct. to the end of Nov.

Red. *High.*—The river rises in Jan. and holds a fair stage until into June. The highest water of the year may occur any time from Feb. to May, and probably in April to May. There is an occasional short rise in late Summer or Fall.

Low.—The river falls in July and runs low as a rule until in Dec. The lowest water for the year may occur in Sept, Oct. or Nov.

The Main River. *High.*—The river begins to rise early in January, and attains a max. stage usually in latter part of April or May, falling in June, July and August.

Low.—The low water occurs from Sept. on to the end of the year, reaching the lowest point, as a rule, in Nov.

Table of Rainfall and Discharge Data for the Principal Watersheds of the Mississippi System.

Watershed.	Rainfall.										Flow per Second.					
	Annual.		Spring.		Summer.		Autumn.		Winter.		Minimum.		Average.		Maximum.	
	Inches. Depth.	Cu. ft. per sec. per sq. mile.	Inches. Depth.	Cu. ft. per sec. per sq. mile.	Inches. Depth.	Cu. ft. per sec. per sq. mile.	Inches. Depth.	Cu. ft. per sec. per sq. mile.	Inches. Depth.	Cu. ft. per sec. per sq. mile.	Total in 1000's of cu. ft.	Cu. ft. per sec. per sq. mile.	Total in 1000's of cu. ft.	Cu. ft. per sec per sq. mile.	Total in 1000's of cu. ft.	Cu. ft. per sec. per sq. mile.
Mississippi above mouth of Minnesota Riv. (19,500 sq. miles)	27·2	2·000	7·1	2·158	10·7	3·296	6·8	1·994	2·7	0·780	3	0·154	13	0·674	50	2·56
Minnesota (16,000 sq. miles)	28·0	2·061	7·0	2·070	11·8	3·476	6·6	1·944	2·6	0·772	0·5	0·031	7·6	0·474	[1]60	3·75
Upper Mississippi above mouth of Missouri Riv. (173,000 sq. miles)	34·7	2·555	9·0	2·650	12·8	3·769	8·2	2·415	4·6	1·355	25	0·144	118	0·688	550	3·17
Missouri (528,000 sq. miles)	19·6	1·443	6·1	1·796	6·4	1·885	4·4	1·296	2·7	0·795	25	0·047	94	0·178	600	1·14
Ohio (214,000 sq. miles)	43·1	3·173	11·9	3·504	11·8	3·925	8·5	2·503	10·9	3·210	35	0·163	204	0·953	1200	5·61
St. Francis (80,000 sq. miles)	41·3	3·041	12 4	3·652	10·2	3·004	8·6	2·533	10·3	3·033	[2]3·5	0·438	17	2·130	[4]36	4·50
White (28,000 sq. miles)	42·0	3·092	13·0	3·828	11·0	3·239	10·0	2·945	8·0	2·356	4·5	0·161	20	0·750	120	4·29
Arkansas (161,000 sq. miles)	28·3	2·082	8·6	2·518	9·3	2·748	6·3	1·864	4·1	1·207	4	0·024	48	0·300	250	1·55
Yazoo (13,000 sq. miles)	53·3	3·924	17·8	5·239	10·9	3·222	8·9	2·621	15·7	4·615	[3]5	0·384	35	2·749	[4]80	6·15
Red (97,000 sq. miles)	38·3	2·798	11·5	3·386	10·2	3·019	8·4	2·485	8·2	2·400	3·5	0·036	50	0·515	180	1·86
Mississippi above its mouth (1,259,000 sq. miles)											175	0·139	664	0·528	1800	1·43

[1] Probably much exceeded at times.

[2] Obtained from a comparison of the Yazoo and White.

[3] Derived chiefly from gaugings by Captain Willard; checked by comparison with the White.

[4] Result chiefly of a comparison with the White, allowing for differences of rainfall and topography.—Somewhat uncertain.

before it reaches the streams. Again, heavy rainfalls are liable to be somewhat local in their extent, when the entire drainage basin of a large river is considered. In the case of the Missouri, for instance, while the early spring rains are falling upon the regions near its mouth, the upper and elevated watershed is supplying comparatively nothing to the flow. The natural tendency of such a condition as this is to pull down the average rate of the high flow per square mile for an extensive drainage area. On account of the above reasons it is not surprising that the northern and large western tributaries of the Mississippi should carry comparatively small rates of maximum flood volume per square mile. To be sure, they have an advantage over the strictly southern rivers in drawing upon large quantities of melting ice and snow which may concentrate the winter precipitation in a brief period of melting. The winter precipitation upon their basins, however, is far lower in rate than for the other three seasons of the year, and the melting occurs chiefly before the heaviest rainfalls, which tend toward the late spring or summer. There result from this simply two freshets, the first due to melting aided by rains, and the second due principally, if not entirely, to rains alone. Between these two freshets occurs a more or less pronounced tendency to a merely fair or average stage of water.

Upon turning to consider the rates of low flow and their causes one is confronted at once with the much smaller annual rainfall upon the entire northern and western portion of the Mississippi watershed. Behind this prominent fact are a number of minor considerations. Thus, the proportionate, and probably the absolute loss from evaporation and absorption by vegetation is greater for regions with a light, than for those with a large rainfall. The proportion of natural storage per square mile in the form of lakes and swamps is smaller for large than for small watersheds. Finally, the climatic conditions are such over the major part of the Mississippi watershed, that the period of light rainfall in the autumn dominates a wide extent of country. So, while it is true that all portions of any one of the large watersheds will not at any one time be giving their maximum flood volume for the year, the converse is not true, for they may uniformly concur in yielding their minimum flows. The entire watershed of the longest tributary of the Mississippi, for instance, may at one and the same time be suffering from a greatly diminished rainfall, and one part of the area cannot be counted upon to maintain the flow while another part is subject to drouth. The above causes readily account for the exceedingly low flow per square mile of 0·047 cubic feet per second from the Missouri, and 0·024 cubic feet from the Arkansas, and for the uniformly low rate of minimum flow from all the smaller streams in the northwestern part of the Mississippi watershed.

Passing now to the extreme upper waters of the river, the upper Mississippi above the mouth of the Minnesota, and the Minnesota itself show certain interesting and instructive differences. The total amount and the distribution of the rainfall is nearly the same for both, the Minnesota having a slightly more pronounced concentration of rainfall in the summer months. The Minnesota is preëminently a prairie stream, whereas the main river is characterized, to an unusual degree, by lakes and swamps. It is not strange, therefore, that the flood-flow per square mile is nearly fifty per cent larger from the Minnesota than from the main stream. Neither is it to be wondered at that the Minnesota dwindles away to 0·031 cubic feet per square mile per second in low water, exhibiting the true character of a prairie stream, while the natural lakes and swamps of the main river hold it, in spite of the low rainfall, up to 0·154 cubic feet per square mile per second.

The upper Mississippi, at the point where it unites with the Missouri to form the lower river, takes high rank in the matter of rates of flow, in spite of its average climatic conditions being essentially those already described as pertaining to the northern and western tributaries. Its high rate of low flow is largely the result of the natural storage in the immense number of lakes and swamps in the States of Minnesota and Wisconsin. This storage affects to a marked degree the main river above St. Paul, the Saint Croix, Chippewa, Wisconsin, and other tributary streams. As a result, these rivers withstand very successfully the depressing effect of the prairie streams like the Minnesota, which enter from the west, and they maintain the low flow at 0·144 cubic feet per second per square mile.* But not alone in its low flow as compared with the climatic conditions, is the upper Mississippi noticeable. Although its average annual rainfall is slight, yet it has heavy summer rains widely enough distributed over its 173,000 square miles of watershed to hold it well up toward the ranks of the high flood-flow tributaries. Also, its spring melting is sufficiently concentrated in point of time to have a very important influence npon the records of flood volume.

The Ohio demands special mention because of pronounced activity among its fellow tributaries. In a hydrological sense

* Attention is here called to the fact that this paper is written throughout with reference to the natural conditions of the Mississippi drainage; the conditions which would pertain if the artificial storage works installed by the United States Government at the sources of the river were not existing. These works, uncompleted as they are, have resulted in maintaining a stage at St. Paul during the low season considerably more than a foot above the natural conditions of the river.

it is the ruling tributary of the Mississippi system. Although it has less than half as large a drainage area as the Missouri, yet its low, high, and average flows all exceed in total amounts the like volumes from the Missouri. In rates per square mile, these flows are only exceeded in the cases of certain southern rivers. In fact, the Ohio is rightly classed with the southern rivers, even granting that the annual melting of snow and ice is a prominent feature upon its basin. It has been pointed out that upon most extended drainage areas, the rate of high flow is pulled down by the averaging of districts where the rains may be falling, with regions that happen at that time to be comparatively dry. Not so for the Ohio. There is a strong tendency for moisture-laden air to be whirled in broad sheets over the watershed clear to the Alleghanies, and deposit heavy rainfalls during the same month over nearly the entire length of the basin. When this is taken into account with the relatively large average rainfall of 43 inches, and with the fact that the winter rains are only slightly less in amount than those of spring, the greatest of the year, and occur at the time when the snow and ice are going out, it is easy to understand why the Ohio should tower far above the other large tributaries of the Mississippi in its rate of high flow. That the Ohio is above even the upper Mississippi in its rate of low flow, is due primarily to its higher annual rainfall, and also to its important southern branches extending into a region of considerable autumn rainfall.

The lower Mississippi, the main channel into which all the tributaries flow, claims final attention. It is the resultant of these tributaries, but a resultant in which the element of time is a potent factor. If all the tributaries were high and low together, it would be easy to compute the high flow or low flow of the main stream by a simple process of summation. Owing, however, to a lack of unanimity among the streams in this respect, it is an exceedingly complicated and, in fact, impossible task to reason out conclusions concerning the flow of the main river simply from the general data for the tributaries. The tributaries do conspire to a considerable degree in producing the low stages of the main river, for the area of light rains in the fall is very widely extended over the Mississippi watershed. All the rivers are not at their lowest during the same time, however, for if they were the aggregate flow would be only 110,000 cubic feet per second, whereas the low water discharge of the Mississippi may be taken at 175,000 cubic feet per second, although lower gaugings have been recorded.

Fortunately for the well-being of the dwellers within the Mississippi valley, the tributary streams differ very widely in their times of flood. A simple calculation shows that if high water occurred simultaneously with them all, the main river would have to carry over three millions cubic feet of water per second to the Gulf. As a matter of fact, it is an extremely rare coincidence for more than two of the large tributaries to be at their highest yearly stages at the same time. The greatest annual flood upon the Ohio, for example, has disappeared before that from the Missouri reaches the Mississippi. Thus the aggregate in the main river is kept down, so that 1,800,000 cubic feet per second may be considered a large flood discharge from the Mississippi. The combination of conditions is such that the lower river usually reaches its maximum volume for the year in April or May, and its lowest stage in October or November. The diagram shows, by a convenient comparison of rates of flow per square mile per second, the resultant effect of all the tributaries upon the main river. The rate of low flow, 0·139 cubic feet per square mile per second, is fairly well up, in spite of the downward pull given by the Missouri and Arkansas. The rate of high flow is kept down to 1·43 cubic feet per square mile per second,—which is only surpassed in smallness in the case of the Missouri,—by the above mentioned lack of coincidence in the times of flood from the various tributaries.