PREPARED IN COOPERATION WITH THE
METROPOLITAN DISTRICT COMMISSION
BOSTON, MASSACHUSETTS

SURFACE WATER

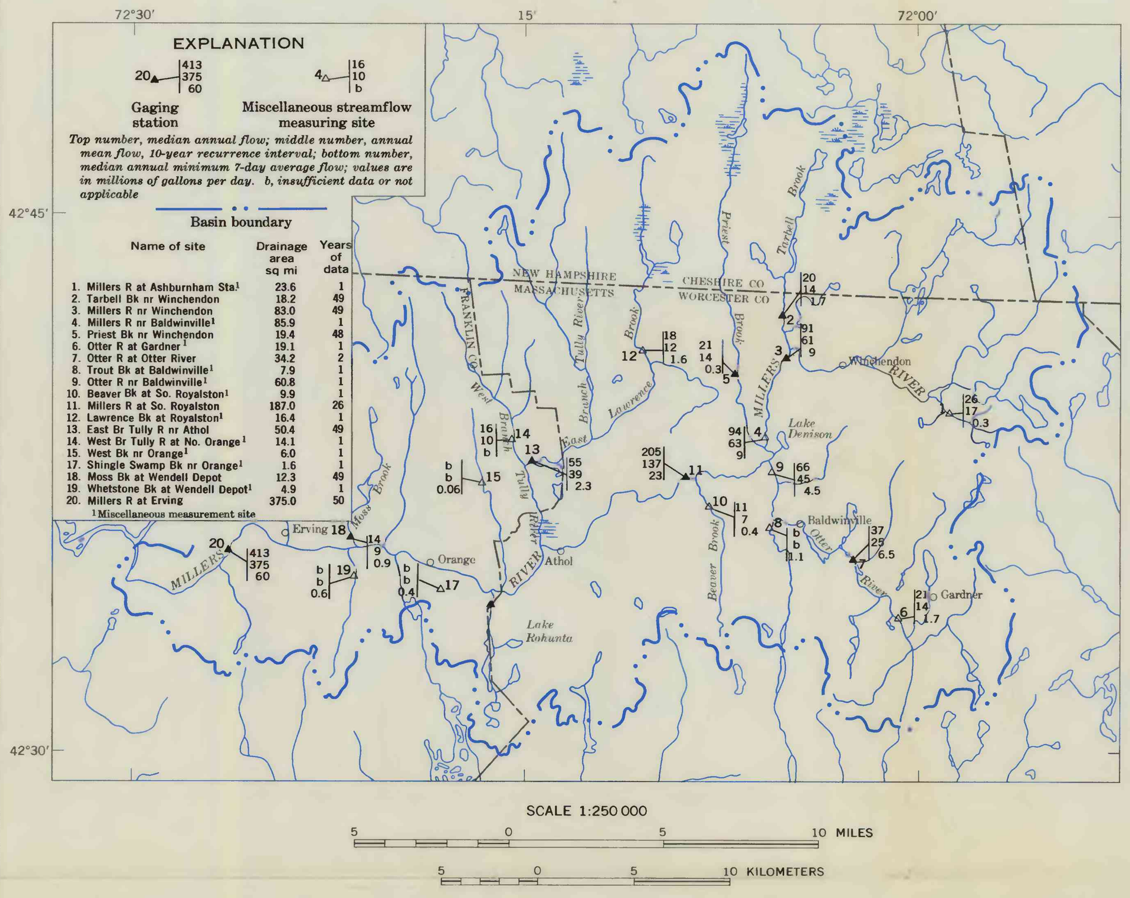


FIGURE 1.—MAP SHOWING MEAN AND LOW FLOW DATA ON THE MILLERS RIVER AND SELECTED TRIBUTARIES. *Based on the climatic year beginning April 1. The annual flows are related to drainage area size. The annual minimum flows are governed by basin characteristics such as lithology*

GAGING STATIONS

There are nine surface-water gaging stations in the Millers River basin, three are located on the main stem and six are on tributary streams (fig. 1). In addition to the nine recording stations, eleven low-flow partial record sites were measured.

The gaging stations on East Branch Tully River and on Millers River at South Royalston are located below flood-control dams and the station on Lake Rohunta outlet near Athol is located below a hydroelectric power dam. The other recording stations and miscellaneous measuring sites, for the most part, are not significantly affected by control. However, where necessary or possible, adjustments for change in storage were made.

MONTHLY AND ANNUAL FLOW AND ITS VARIABILITY

The variation of flow is shown by a graph of mean monthly discharges (fig. 2) using East Branch Tully near Athol as an example.

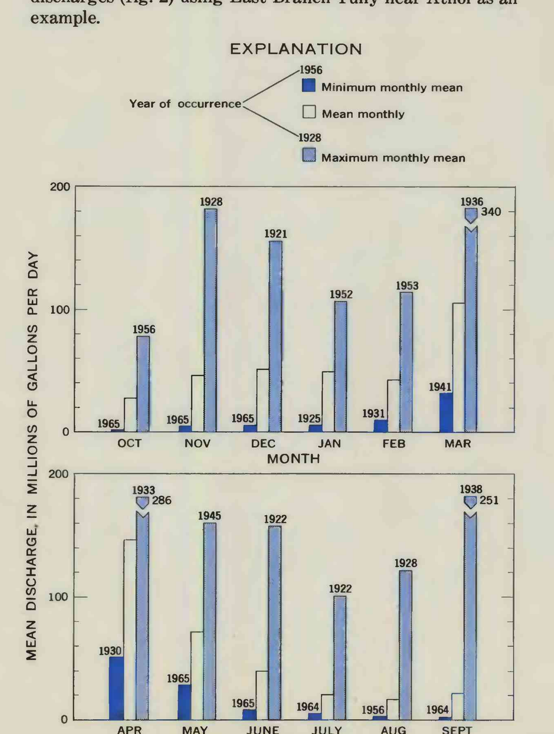


FIGURE 2.—GRAPH SHOWING VARIATION OF MONTHLY FLOWS, EAST BRANCH TULLY RIVER NEAR ATHOL (1917-65). *The graph is an example of the typical variation of mean monthly flows over the year throughout the basin.*

The period of high runoff normally occurs in the spring, however high flows of short duration may occur at any time as a result of intense cyclonic or convective storms. Low flows are prevalent during middle and late summer. The variation of annual flows is illustrated in figure 3 for the Priest Brook near Winchendon gaging station. Typical of the streams in the basin, for the period of record (thru 1965), Priest Brook's highest annual mean flow (35.5 mgd in 1920) is about four times the lowest annual mean discharge (9.2 mgd in 1930).

The mean annual flows in the Millers River basin are closely related to the size of the corresponding drainage area; for instance, the median annual flows (2-year recurrence interval in figure 1) average 1.09 mgd per sq mi. The location number, name, and drainage area size of gaging sites are shown in figure 1. A table of the average frequency values for annual flows of the seven long-term gaging stations is given as:

Recurrence interval, in years	2	5	10	20	50
Discharge, in mgd per sq mi	1.09	0.86	0.73	0.63	0.50

The frequency values for annual flow at each of the seven long-term gages are shown in table 1.

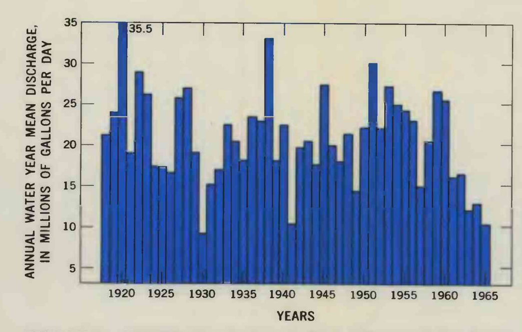


FIGURE 3.—HYDROGRAPH OF ANNUAL MEAN DISCHARGES OF PRIEST BROOK NEAR WINCHENDON. *The hydrograph is an example of the variation of annual mean flows in the basin from year to year.*

TABLE 1.—*Frequency values of mean annual flow for the seven long-term gaging stations, in million gallons per day per square mile (mgd per sq mi).*

Location number on figure 1	Recurrence interval, in years 2	5	10	20	50
2	1.06	0.85	0.74	0.66	0.56
3	1.12	.88	.76	.66	.54
5	1.11	.87	.74	.64	.51
11	1.10	.85	.71	.59	.44
13	1.08	.86	.73	.63	.50
18	1.11	.86	.72	.60	.47
20	1.08	.85	.72	.61	.48

Flow duration curves for seven long-term stations (fig. 4) depict the characteristics of each basin. The upper end of the curve is indicative of high flow and shows the storage character of the basin, the flatter the slope the greater the storage. The slope of the tail or lower end of the curve is the result of basin geology and storage; the greater the storage the flatter the slope of the tail.

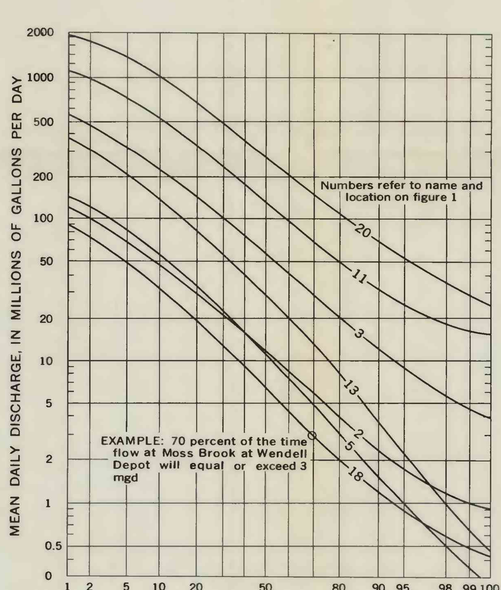


FIGURE 4.—DURATION CURVES OF GAGING STATIONS IN THE BASIN. *The slope of the extremes of the curves reflect basin characteristics.*

LOW-FLOW CHARACTERISTICS

Low flows are derived largely from ground water and/or channel storage. One of the most useful means of characterizing low flows is by the magnitude and frequency of selected low-flow periods. The slope of the frequency curve is a function of basin storage, the flatter slope usually depicts more available storage than a steeper slope. Magnitude of average low flows for minimum annual (April 1 climatic year) consecutive periods at selected frequencies are listed in table 2 for the long-term gaging stations and typical examples of plotting are shown in figures 5 and 6.

TABLE 2.—*Magnitude and frequency of low streamflows at selected sites.*

Location number refers to figure 1	Number of consecutive days	Discharge in millons of gallons per day, Recurrence interval, in years: 2	5	10	20	50
2	1	1.2	0.56	0.39	0.27	0.17
	3	1.4	.78	.53	.36	.24
	7	1.7	.97	.71	.47	.33
	14	2.1	1.2	.84	.61	.43
	30	2.9	1.4	1.0	.78	.54
	60	3.2	1.7	1.3	.97	.71
	90	3.7	2.1	1.6	1.2	.90
	120	4.6	6.2	1.6	1.5	1.2
	150	5.6	3.4	2.6	1.9	1.4
	183	6.6	3.9	2.8	2.1	1.5
	274	10	6.5	4.8	3.7	2.7
3	1	5.6	3.7	2.9	2.4	1.9
	3	7.1	4.4	3.4	2.8	2.3
	7	9.0	5.3	4.0	3.4	2.7
	14	12	6.2	4.6	3.9	3.2
	30	16	7.8	5.6	4.6	3.8
	60	19	9.0	6.5	5.4	4.4
	90	24	13	9.0	6.5	5.1
	120	28	16	11	7.8	6.2
	150	33	19	14	10	8.4
	183	38	23	17	14	12
	274	54	36	27	21	15
5	1	.84	.35	.20	.12	.07
	3	.90	.40	.24	.14	.08
	7	1.0	.50	.32	.20	.12
	14	1.4	.65	.43	.28	.19
	30	1.9	.97	.63	.44	.26
	60	2.8	1.3	.84	.52	.28
	90	3.2	1.5	.97	.54	.29
	120	4.1	2.0	1.3	.84	.52
	150	4.5	2.3	1.7	1.2	.90
	183	6.3	3.7	2.7	2.1	1.5
	274	9.7	6.5	4.7	3.9	2.9
11	1	19	13	10	8.4	6.3
	3	21	16	14	12	10
	7	23	17	16	14	13
	14	25	19	17	15	14
	30	29	21	18	16	15
	60	37	23	19	17	15
	90	44	26	21	18	16
	120	54	31	25	21	18
	150	63	38	32	27	23
	183	76	48	39	32	26
	274	123	78	62	46	34
13	1	1.5	.49	.28	.16	.08
	3	1.9	.84	.52	.32	.19
	7	2.3	1.2	.78	.49	.32
	14	3.0	1.5	1.0	.71	.45
	30	4.1	2.0	1.4	.97	.65
	60	6.0	2.8	1.8	1.4	.97
	90	7.8	4.0	2.8	2.2	1.6
	120	10	5.6	3.9	3.0	2.2
	150	14	7.8	6.0	4.7	2.9
	183	17	9.7	6.5	4.8	3.2
	274	27	17	14	10	7.8
18	1	0.71	0.44	0.34	0.26	0.20
	3	.78	.48	.36	.28	.21
	7	.90	.52	.39	.30	.22
	14	1.0	.60	.45	.36	.27
	30	1.2	.71	.52	.41	.32
	60	1.6	.97	.71	.55	.43
	90	2.1	1.1	.84	.65	.48
	120	2.6	1.4	.97	.78	.63
	150	3.6	2.1	1.6	1.3	.97
	183	4.5	2.8	2.2	1.8	1.4
	274	7.1	4.3	3.1	2.3	1.6
20	1	28	14	9	6.5	4.6
	3	49	27	22	17	13
	7	60	38	30	24	18
	14	72	46	36	29	22
	30	85	56	41	34	27
	60	94	58	45	37	32
	90	97	62	49	41	35
	120	143	71	56	46	38
	150	139	87	68	56	44
	183	202	103	81	68	54
	274	252	162	123	97	71

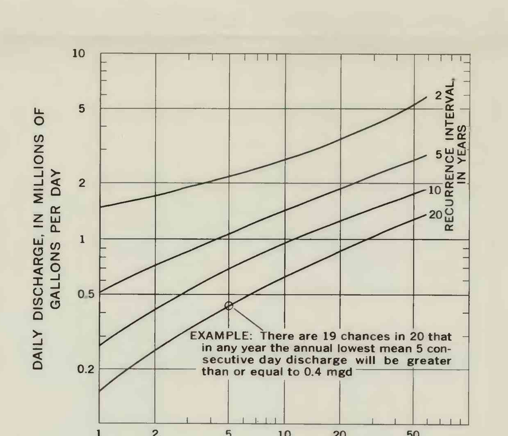


FIGURE 5.—GRAPH SHOWING MAGNITUDE AND DURATION OF SELECTED LOW FLOWS FOR EAST BRANCH TULLY RIVER NEAR ATHOL. *The chances of occurrence of low flows may be determined for any number of consecutive days.*

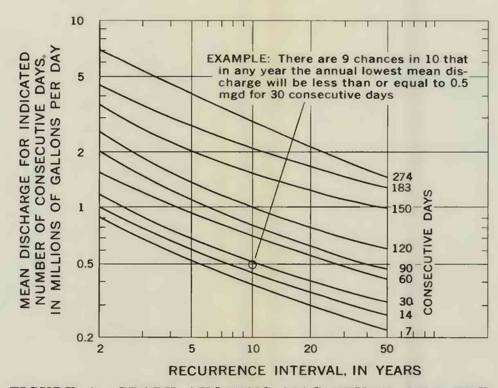


FIGURE 6.—GRAPH SHOWING MAGNITUDE AND FREQUENCY OF SELECTED LOW-FLOW DISCHARGES FOR MOSS BROOK AT WENDELL DEPOT. *The annual lowest mean daily discharge for any recurrence interval and for the indicated consecutive days may be determined from the curves.*

To describe the low flow at ungaged sites in the Millers River basin, additional tributary streams were measured during low-flow periods and correlated with long-term records of gaged streams. The results of the low flow investigations at partial record low flow sites are shown in figure 1. The accuracy of the low-flow estimates for the ungaged streams is not easily assessed, however the closer the slope and coefficient of correlation are to unity the more similar are the low-flow characteristics.

STORAGE ANALYSES

Many demands on water for domestic use, industry, waste dilution and irrigation are greater than minimum streamflow. Augmentation of low flows may be accomplished by storage of higher flows.

Storage for specified draft rates at a gaged site were determined from the low flow frequency relations of table 2 as described by Riggs (1966). Figure 7 shows typical draft-storage recurrence curves.

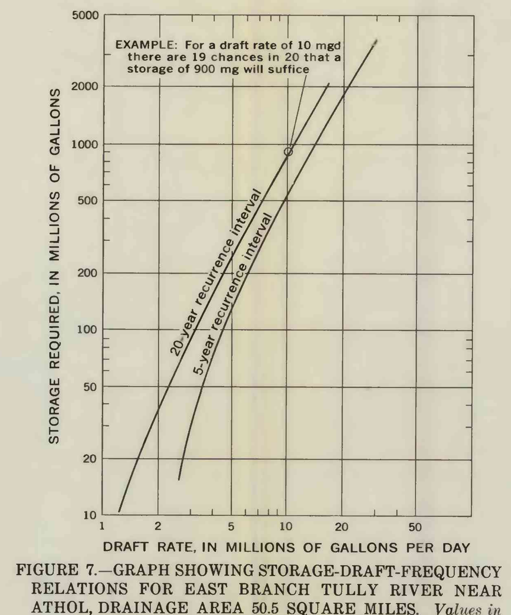


FIGURE 7.—GRAPH SHOWING STORAGE-DRAFT-FREQUENCY RELATIONS FOR EAST BRANCH TULLY RIVER NEAR ATHOL, DRAINAGE AREA 50.5 SQUARE MILES. *Values in table 3 were scaled from similar curves and adjusted to a square-mile basis. Evaporation adjustment is not included in storage values.*

To determine storage required at the 11 low flow partial record sites (fig. 1) the median annual minimum 7-day average flows, as determined from correlations with nearby gaged sites, was selected as a parameter. The median 7-day flow, the storage required, and selected draft rates of the gaged sites were converted to a square mile basis and the curves in figure 8 were drawn. The median 7-day flows (shown on fig. 1) of the partial record sites were converted by dividing by their drainage area, and the storage values were picked from curves in figure 8 for the 20-year recurrence interval (similar curves were used for the 5-year recurrence interval) and are listed in table 3. Therefore, in order to use figure 8 for determining storage at ungaged sites, it is necessary to obtain low flow measurements at the site.

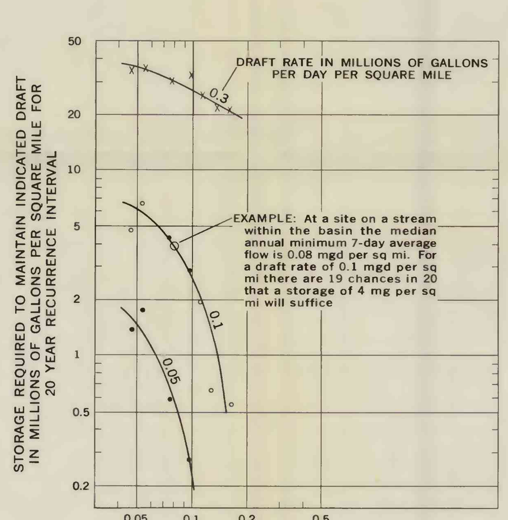


FIGURE 8.—GRAPH SHOWING DRAFT-STORAGE CURVES FOR THE 20-YEAR RECURRENCE INTERVAL, MILLERS RIVER BASIN. *Using the median minimum 7-day flow as a parameter, storage at the 20-year recurrence interval and for select draft rates may be determined over the range of the curves. Evaporation adjustment is not included in storage values.*

TABLE 3.—*Storage analysis[1] for water supply at selected sites.*

Location number refers to figure 1	Drainage area (sq mi)	Draft rate (mgd per sq mi)	Storage required to maintain draft, mg per sq mi, Recurrence interval: 5-year	20-year
1	23.6		Not applicable	
2	18.2	0.05	0.02	0.27
		.1	.71	2.9
		.3	22	34
3	83	.05	.01	.06
		.1	.47	1.9
		.3	14	26
4	85.9	.05	0	.11
		.1	.55	2.4
		.3	13	27
5	19.4	.05	.25	1.7
		.1	1.8	6.5
		.3	25	35
6	19.1	.05	0	.35
		.1	.85	3.2
		.3	17	29
7	34.2		Not applicable	
8	7.8		Not applicable	
9	60.8	.05	.30	.66
		.1	1.3	4.3
		.3	21	32
10	9.9	.05	.30	1.6
		.1	2.4	6.2
		.3	26	36
11	187	.05	0	0
		.1	.06	.64
		.3	15	21
12	16.4	0.05	0	0.22
		.1	.66	2.7
		.3	15	28
13	50.4	.05	.28	1.3
		.1	2.4	4.8
		.3	22	35
14	14.1		Insufficient data	
15	6.0		Not applicable	
16	20.3		Highly controlled	
17	1.6		Not applicable	
18	12.3	.05	.06	.58
		.1	1.5	4.3
		.3	22	30
19	4.9	0.5	0	0
		.1	.23	1.4
		.3	8.5	24
20	375	.05	0	.02
		.1	.08	.53
		.3	13	22

[1] Values do not include evaporation.

The volumes of storage shown in table 3 do not allow for evaporation from reservoir surface, dam or inundated area seepage, or reduction in storage capacity from reservoir sedimentation.

Evaporation may be determined by using pan evaporation as an index. Seepage can only be evaluated after the dam site has been selected; however, precipitation on the surface of the reservoir may offset the seepage losses to some extent. Sedimentation in the reservoir generally may be evaluated from sediment load of streams given in table 2, sheet 4.

DIVERSION ANALYSES

Flow of most streams is subject to prior water claims for industry, waste dilution and/or domestic use and a sophisticated analysis should consider requirements for users downstream. In cases where water needs are less than water supply, excess water may be diverted to other basins. A graphical representation of a probability analysis of volume of diversion from daily discharges, presented on an annual basis, above a range of minimum flows for downstream needs is shown in figure 9.

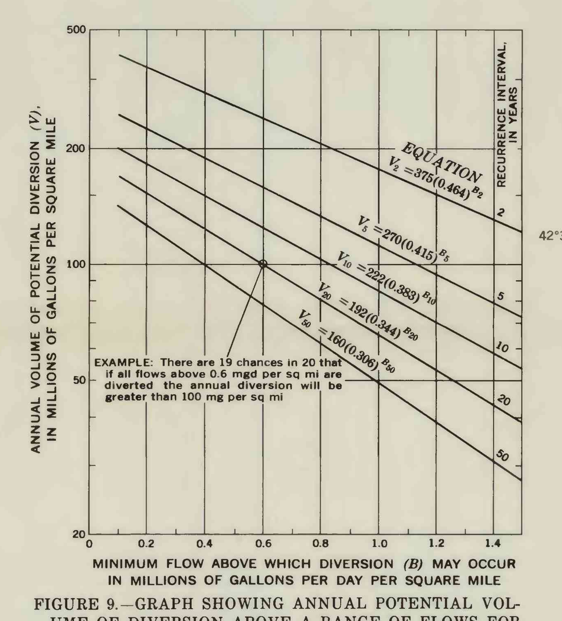


FIGURE 9.—GRAPH SHOWING ANNUAL POTENTIAL VOLUME OF DIVERSION ABOVE A RANGE OF FLOWS FOR SELECTED FREQUENCIES. *For a particular site the volume of diversion (V) above a predetermined flow (B) for a selected recurrence interval is determined by multiplying the values of (V) and (B) by the area draining (square miles) to the site.*

The curves in figure 9 were computed from the mean daily records of the seven long-term gaging stations in the basin.

An example of further application of the diversion analysis is shown in figure 10.

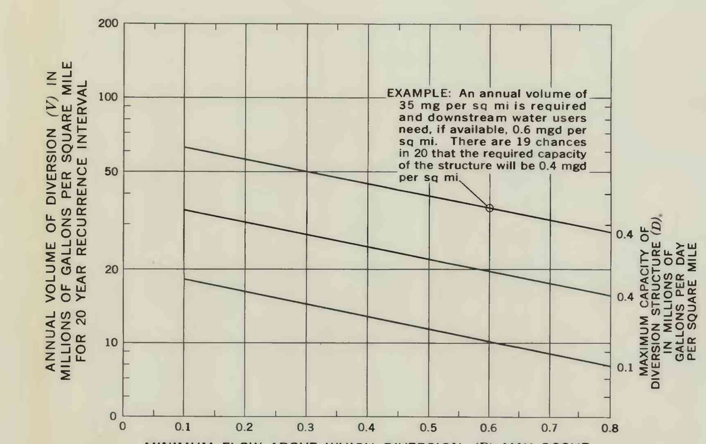


FIGURE 10.—GRAPH SHOWING VOLUME OF DIVERSIONS ABOVE A SELECTED FLOW AT THE 20-YEAR RECURRENCE INTERVAL. *The volume (V) for a diversion (D) above a flow (B) may be determined with an assurance, on the average, that 19 times in 20 the event will occur in any year.*

FLOOD FLOWS

Knowledge of magnitude and probable frequency of recurrence of floods is necessary for designing and locating structures such as dams, bridges, culverts, highways, waterworks, sewage-disposal plants and for flood insurance and flood zoning. From information on probable flood size, in many cases the problem becomes one of economics involving costs of building and maintaining a structure of a selected design compared to the cost of other designs.

A frequency curve for a gaging-station record applies only to the site of the station, and, generally, the information is needed for an ungaged point. For ungaged sites, over 10 square miles drainage, a method using drainage area and stream slope for calculating the probable magnitude of floods at various recurrence intervals on a regional basis, has been devised (Knox and Johnson, 1965). The equations for several recurrence intervals used to compute magnitudes of floods for the partial-record sites in the basin are:

Equation

$$Q_{2.33} = 2.06\ AS^{0.5} \quad Q_{25} = 6.16\ AS^{0.5}$$
$$Q_{5} = 2.19\ AS^{0.5} \quad Q_{50} = 8.14\ AS^{0.5}$$
$$Q_{10} = 3.95\ AS^{0.5}$$

where Q is the magnitude of flow in mgd, the subscript on Q is the recurrence interval, A is the area of the drainage basin, in square miles, and S is the channel slope, in feet per mile (S is determined from elevations of points on the stream 85 and 10 percent of the total stream length above the site).

The magnitude of the mean annual flood (2.33 recurrence interval), the 10-, 25-, and 50-year floods and the maximum observed flood are shown in figure 11 for selected sites over the basin. Values of flood flow at long-term gaging stations were obtained from the plotted frequencies determined from discharge records. Values of flood flow at the partial record sites were computed from equations listed above.

Two flood control dams in the basin are: Tully dam, located on the East Branch Tully River, having a drainage area of 50.4 square miles and the reservoir has a capacity of 22,000 acre-feet; and Birch Hill dam, located above South Royalston on the Millers River with a drainage of 175 square miles and a reservoir capacity of 49,900 acre-feet.

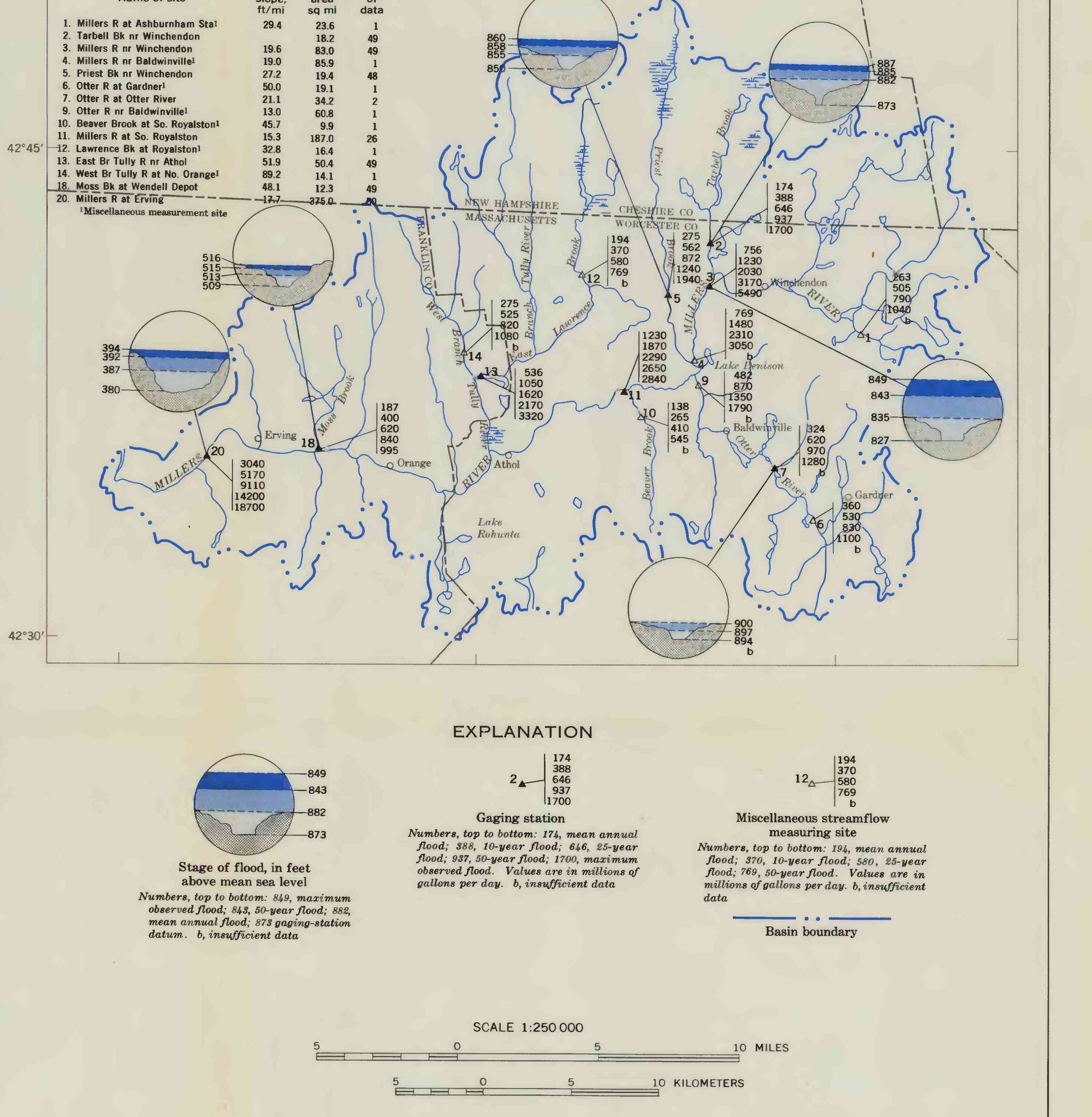


FIGURE 11.—MAP SHOWING FLOOD FLOWS OVER THE BASIN. *Based on the water year beginning October 1. The spatial variation of flood flow is related to drainage area size and stream slope. The flood stages shown may be used in conjunction with a topographic map to determine areas of flood inundation above the gaging stations.*

FLOOD-VOLUME-DURATION ANALYSES

Defining the probability of recurrence of flood volumes for various durations of time is useful in planning design, construction and operation of projects which include storage of floodwaters.

Statistical analyses have been used to determine flood probabilities for various durations applicable to most sites in the Millers River basin. The equation developed was, $Q = b_o A^b$, where Q is the flood volume, in mgd, A is the drainage area, in sq mi and b_o and b are regression constants determined from table 4. The limitations imposed are: (1) the drainage area should exceed 10 square miles and (2) relatively no man-made control of high flows exists. All values were computed from records using the water year (Oct. 1 to Sept. 30).

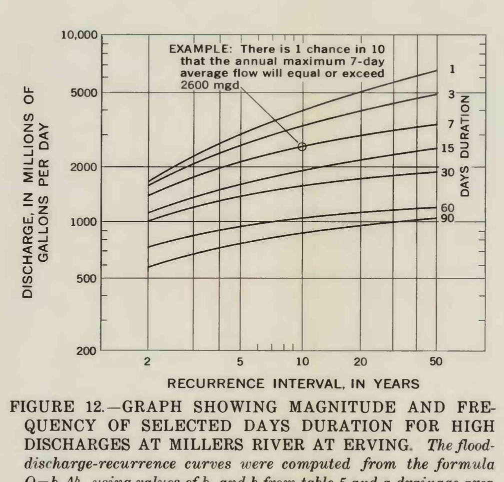


FIGURE 12.—GRAPH SHOWING MAGNITUDE AND FREQUENCY OF SELECTED DAYS DURATION FOR HIGH DISCHARGES AT MILLERS RIVER AT ERVING. *The flood-discharge-recurrence curves were computed from the formula $Q = b_o A^b$, using values of b_o and b from table 4 and a drainage area (A) of 375 square miles.*

TABLE 4.—*Values of b and b_o for the flood-volume equation, $Q = b_o A^b$*

Duration, in days	Values of b	Values of b_o for recurrence interval, in years: 2	5	10	20	50
1	0.83	15.5	26.5	35.5	45.2	58.8
3	.89	11.6	17.4	22.0	26.5	32.3
7	[1].93	7.75	11.6	13.6	15.5	[1]18.1
15	.93	5.81	8.40	9.69	11.0	12.9
30	.97	4.52	5.81	6.46	7.11	7.75
60	.97	3.10	3.94	4.33	4.65	5.04
90	.97	2.45	3.23	3.55	3.88	4.33

[1] Example: There is 1 chance in 50 (50-year recurrence interval) that in any year the annual 7-day average maximum discharge for a 75 sq mi drainage area (A) will equal or exceed, $Q = 18.1\ (75)^{0.93} = 1000$ mgd, where $b_o = 18.1$ and $b = 0.93$.

From table 4 the basic flood-discharge-recurrence curves for selected durations and for a selected site may be calculated, figure 12 shows an example. From the magnitude and frequency curves, it is possible to derive other relationships which have practical applications to flood-control projects. For example, curves showing the annual highest volume of flow for any duration of days and for a selected recurrence interval can be drawn as shown in figure 13. The curves in figure 13 are obtained by multiplying the magnitude of flow (mgd) by its respective duration of days at a selected recurrence interval to obtain the volume of flow (mg), at the specified recurrence interval. Then volume is plotted against days and a smooth curve drawn. On the curve (fig. 13) tangent lines, the slope of which is reservoir outflow, may be drawn. The point of tangency defines the critical period or time during which storage in the reservoir increases as the flood progresses and the intercept is the required storage.

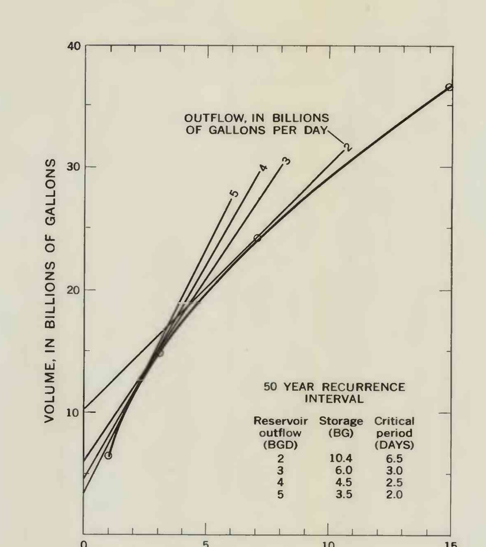
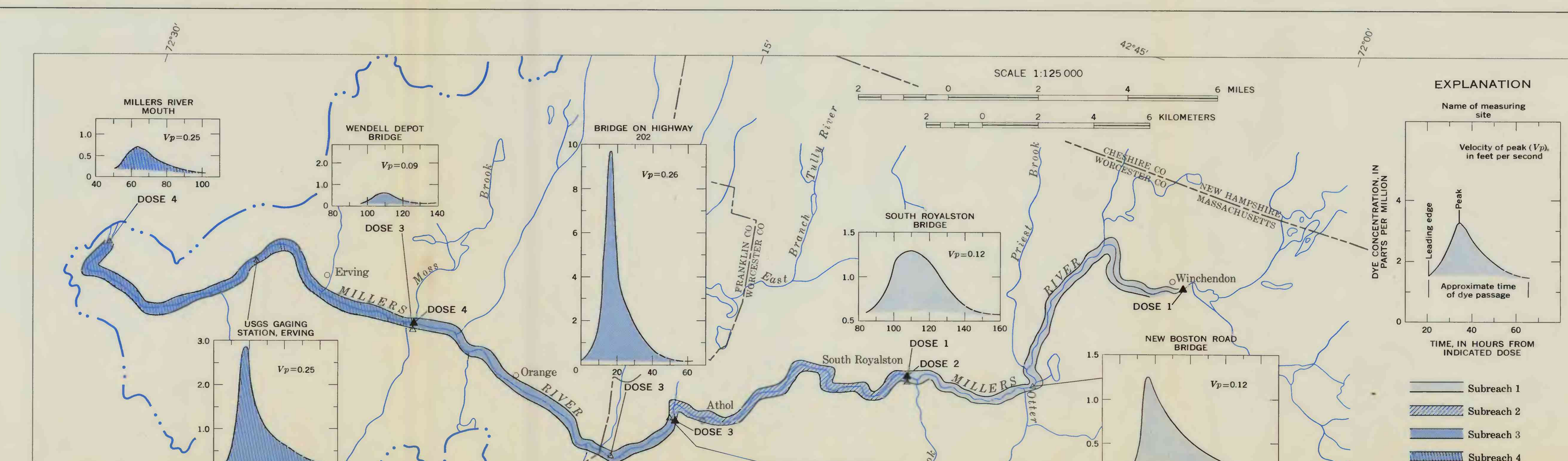


FIGURE 13.—GRAPH SHOWING VOLUME-DURATION CURVE, 50-YEAR RECURRENCE INTERVAL, RESERVOIR OUTFLOWS 2-5 BILLIONS OF GALLONS PER DAY FOR MILLERS RIVER AT ERVING. *From the curve the storage required for various reservoir outflows can be determined and also the critical period or time during which reservoir storage increases as the flood progresses.*



MAP SHOWING TIME-OF-TRAVEL VERSUS DYE CONCENTRATION FOR AUGUST STUDY
Streamflow is equaled or exceeded 95 per cent of the time.

TIME-OF-TRAVEL ON THE MILLERS RIVER

The predicted rate or time-of-travel for dissolved or suspended material in the Millers River has been estimated by using fluorescent dye tracing techniques. A 30-percent solution of Rhodamine B dye was added to the river and the progress of the dye followed by measuring dye concentrations at points downstream from dosing sites (the location where the dye was added). The river was divided into four subreaches for doing the tests (Time of Travel Map) and each subreach had from one to four sites where dye concentration was measured.

The rate at which a contaminant will travel is a function of the discharge of the river. To obtain a relation between river discharge and time-of-travel, the travel-time of the Millers River was determined for a low discharge and a higher discharge (fig. 14). The total length of river studied was 34.5 miles and for the low discharge study (August 1965) it took the dye peak 336.8 hours to travel the distance but only 63.0 hours was required during the higher discharge study (April 1966).

A useful relation for estimating the time-of-travel for stream discharges greater than those of the August 1965 study and less than those of the April 1966 study is shown in figure 15.

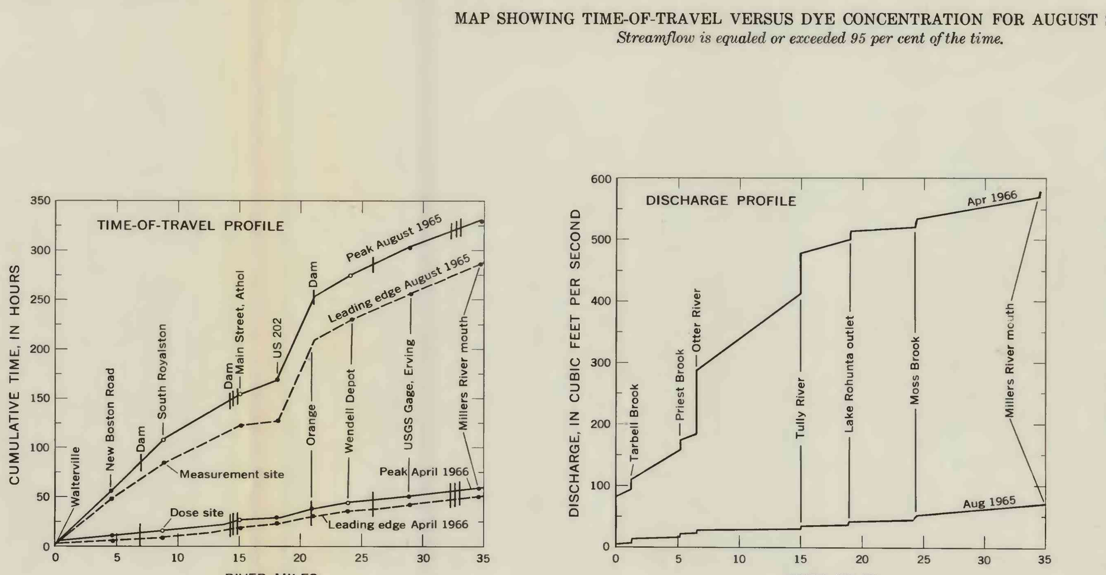


FIGURE 14.—GRAPHS SHOWING RELATIONS BETWEEN TIME, DISCHARGE AND DISTANCE FOR AUGUST 1965 AND APRIL 1966 STUDIES. *Flow for the August 1965 study is equaled or exceeded about 95 per cent of the time and about 35 percent of the time for April 1966.*

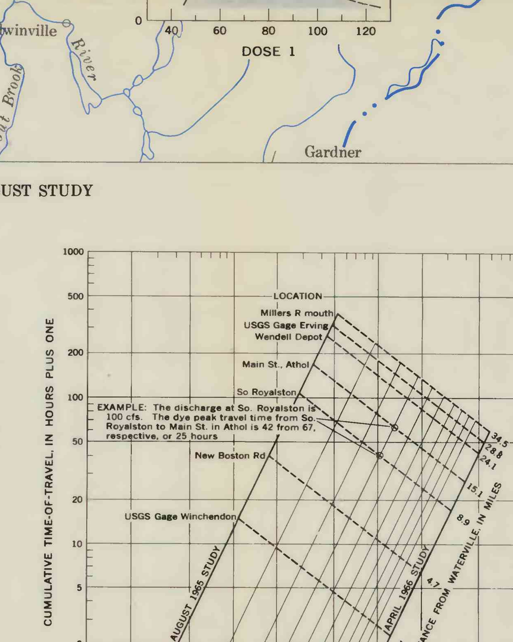


FIGURE 15.—GRAPH SHOWING TIME-OF-TRAVEL VERSUS DISCHARGE FOR THE MILLERS RIVER. *Having the discharge at any of the above indicated locations the time-of-travel may be approximated to any other downstream location or from any other upstream location.*

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