Determination Of Base-Flow Characteristics At Selected Streamflow-Gaging Stations On The Mad River, Ohio

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CONVERSION FACTORS

Multiply	By	To obtain
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
inch (in.)	25.4	millimeter
cubic foot per second (ft³/s)	0.02832	cubic meter per second
square mile (mi²)	2.590	square kilometer

Temperatue can be converted to degrees Celsius (°C) or degrees Fahrenheit (°F) by the equations:

$$°C = 5/9 (°F - 32)$$
$$°F = 9/5 (°C) + 32.$$

Determination of base-flow characteristics at selected streamflow-gaging stations on the Mad River, Ohio

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Abstract

This report describes the results of a study to estimate characteristics of base flow and sustained ground-water discharge at five streamflow-gaging stations on the Mad River in Ohio. The five streamflow-gaging stations are located at Zanesfield, near Urbana, at St. Paris Pike (at Eagle City), near Springfield, and near Dayton.

The median of the annual-mean base flows, determined by means of hydrograph separation, ranged from 0.64 $(ft^3/s)/mi^2$ (cubic feet per second per square mile) at Zanesfield to 0.74 $(ft^3/s)/mi^2$ at St. Paris Pike. The median percentage of annual total streamflow attributed to base flow ranged from 61.8 percent at Zanesfield to 76.1 percent near Urbana.

Estimates of an upper limit (or threshold) at which base flows can be considered to be composed predominately of sustained ground-water discharge were made by constructing and analyzing base-flow-duration curves. The sustained ground-water discharges (base flows less than or equal to the estimated sustained ground-water-discharge thresholds) are assumed to originate from ground-water-flow systems that are minimally affected by seasonal climatic changes. The median sustained ground-water discharge ranged from 0.11 $(ft^3/s)/mi^2$ at Zanesfield to 0.26 $(ft^3/s)/mi^2$ at St. Paris Pike (at Eagle City) and near Springfield. The median sustained ground-water discharge, expressed as a percentage of the median annual-mean base flow, ranged from 17.2 percent at Zanesfield to 38.6 percent near Springfield.

INTRODUCTION

Streamflow in Ohio's Mad River has long been recognized as having an unusually large base-flow (ground-water discharge) component (Leverett, 1902). As a consequence, any attempt to understand the overall discharge or transport characteristics of the Mad River requires a good understanding of its base-flow characteristics and their relation to the total streamflow.

Base flow can originate from a combination of local, intermediate, and regional ground-water flow systems within an aquifer system. Sustained ground-water discharge (discharge to streams from deep, stable regional and possibly intermediate ground-water flow systems) is affected minimally by seasonal climatic changes and consequently is of particular interest to the water resources community.

Purpose and Scope

This report presents the results of a study to (1) provide quantitative information on the contribution of surface runoff and base flow to gross streamflow at selected streamflow-gaging stations on the Mad River, (2) develop flow-duration curves for the base flow component, (3) estimate the discharge below which the base flow can be considered to be composed primarily of sustained ground-water discharge, and (4) determine summary statistics of the sustained ground-water discharges.

Terminology

An aquifer is a geologic formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs (Lohman and others, 1972). An aquifer can be composed of local, intermediate, and regional ground-water-flow systems. These flow systems are differentiated primarily based on the proximity of the recharge areas to the discharge areas. In a local system of ground-water flow, recharge and discharge areas are adjacent to each other. In an intermediate flow system, recharge and discharge areas are separated by one or more topographic highs or lows. In a regional system, recharge areas are along ground-water divides, and discharge areas lie at the bottom of drainage basins (Tóth, 1963).

Base flow is the component of streamflow originating from ground-water discharge (Todd, 1980). Ground-water discharge refers to discharge to streams from a combination of local, intermediate, and regional ground-water-flow systems. In the context of this report, base flow is synonymous with the terms ground-water runoff (Todd, 1980) and effective recharge (Rutledge, 1991).

Sustained ground-water discharge refers to discharge to streams from deep, stable regional and possibly intermediate ground-water-flow systems; that is, ground-water-flow systems that are affected minimally by seasonal climatic changes (Eberts, in press).

Bank storage refers to the variable amount of water stored in the stream banks during stage fluctuations (Singh, 1968).

A flow-duration curve is a cumulative frequency curve that shows the percent of time specified discharges were equaled or exceeded during a given period (Searcy, 1959).

Hydrograph separation is the decomposition of streamflow into components of surface runoff and base flow.

A water year is a continuous 12-month period selected to present data relative to hydrologic or meteorologic phenomena during which a complete annual hydrograph cycle normally occurs (Paulson and others, 1991). The water year used by the U.S. Geological Survey (USGS) runs from October 1 through September 30, and is designated by the calendar year in which it ends.

Geohydrologic Setting

The Mad River is located in west-central Ohio and drains approximately 656 mi^2 (fig. 1). Its headwaters are in Logan County and it flows south and west through Champaign, Clark, and Greene Counties to its confluence with the Great Miami River in Montgomery County. Average annual precipitation in the Mad River basin ranges from about 35 to 38 in. with average annual temperatures ranging from about 51 to 53 °F (Harstine, 1991).
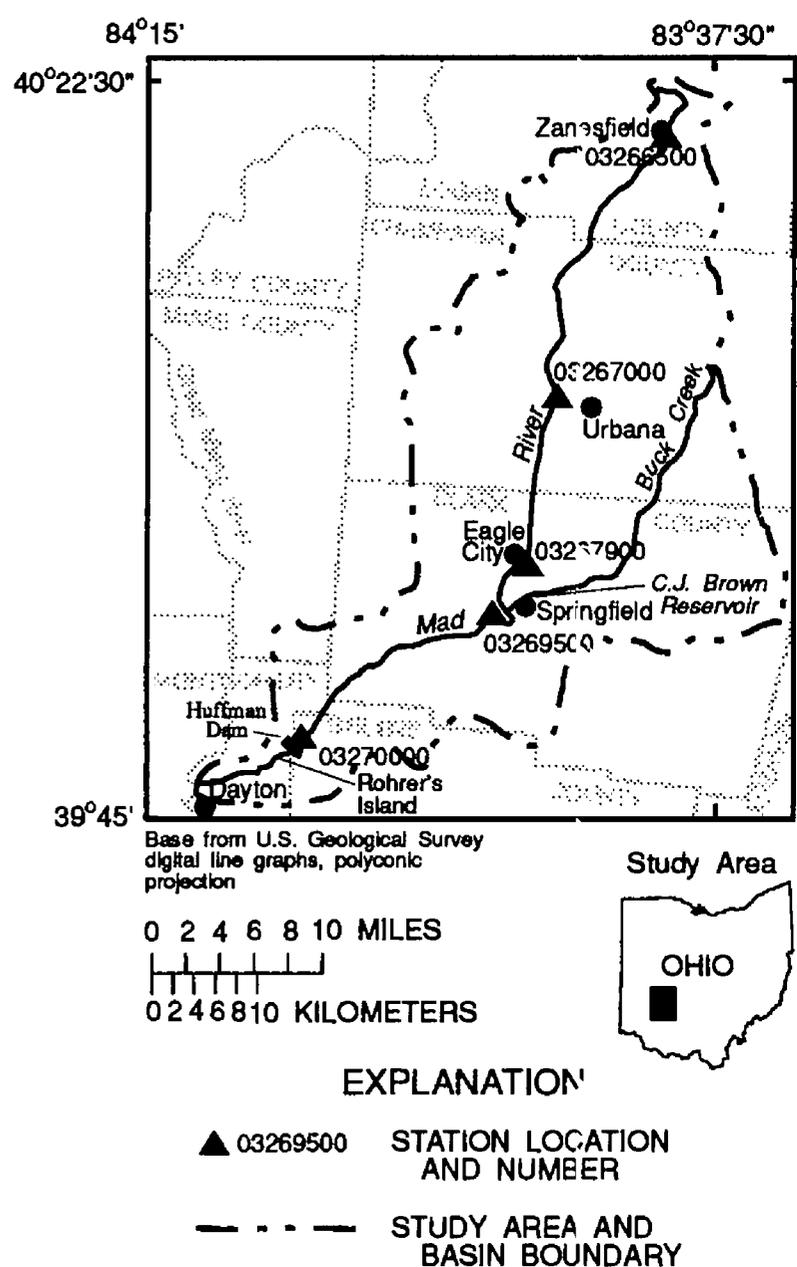
Figure 1. Location map showing study area.

The Mad River occupies a broad trough-like valley of preglacial and interglacial origin with most of its course lying between morainal ridges deposited by the Miami and Scioto lobes of the Wisconsin glacier (Cross and Hedges, 1959). The valley fill consists largely of permeable sand and gravel deposited as kames, kame terraces, high-level outwash, and valley-train deposits (Cross and Feulner, 1964). The valley fill

is constricted by bedrock gorges in the vicinity of the city of Springfield and near the boundary between Greene and Montgomery Counties (at Huffman Dam). The gorge through which the stream passes at Springfield is cut in limestone whereas the gorge at Huffman Dam cuts through limestone and shale. Both gorges have relatively impermeable bedrock walls (Cross and Feulner, 1964).

DETERMINATION OF BASE-FLOW CHARACTERISTICS

Selection of Streamflow-Gaging-Station Records

Records from streamflow-gaging stations on the Mad River were selected for analysis based on the following criteria: (1) the gaging station must have at least 10 years of daily streamflow record, (2) streamflow during low-flow periods must not be appreciably affected by regulation, and (3) the time period analyzed must span both wet and dry periods. Five streamflow-gaging stations (listed in Table 1) met these criteria.

Estimation of Daily Mean Base Flow

The USGS computer program HYSEP (Sloto, 1988) was used to estimate daily mean base flows at the five Mad River streamflow-gaging stations listed in table 1. HYSEP is an implementation of hydrograph-separation algorithms originally developed by Pettyjohn and Henning (1979) for use on Ohio streams.

The local-minimum method of hydrograph separation was chosen for this study because it provides the lowest (most conservative) daily mean base-flow estimate of the hydrograph-separation algorithms implemented in HYSEP. In the local-minimum method, the lowest discharge value (the local minimum) is determined for a fixed-length time interval. The position of the center of the interval is then incremented 1 day and the local minimum is determined again. This process is repeated until the time period being analyzed has been exhausted.

Discharge values are then calculated between each local minimum by linear interpolation.

Table 1. Hydrologic and sustained ground-water-discharge data for selected streamflow-gaging stations on the Mad River, Ohio
[ft^3/s, cubic feet per second; mi^2, square mile]

Station number	Station on Mad River	Drainage area (mi^2)	Period analyzed (water years)	Sustained ground-water discharge threshold (ft^3/s)
03266500	At Zanesfield	731	1947-79	0.9
03267000	Near Urbana	162	1926-31 1940-92	44
03267900	At St. Paris Pike	310	1966-92	93[a]
03269500	Near Springfield	490	1915-92	140
03270000	Near Dayton	635	1916-21 1925-92	175

[a]Threshold determined from duration characteristics adjusted by means of index-station method using station 03269500

The time interval used in the HYSEP program is determined empirically as:

$$I = 2A^{0.2},$$

where I is the time interval, in days; and A is the drainage area in square miles. The time interval (I) is rounded to the nearest odd integer in the range of 3 to 11.

The assumption that the base-flow recession continues after the time when surface runoff begins is implicit in the local-minimum method. Consequently, base-flow estimates derived by this method reflect the process of bank storage (Nathan and McMahon 1990).

HYSEP computes an annual mean base flow for each year analyzed. The median of the annual mean base flows and the median percentage of annual total streamflow attributed to base flow for the five Mad River streamflow-gaging stations are reported in table 2.

Table 2. Selected base-flow statistics for streamflow-gaging stations on the Mad River, Chio
[ft³/s, cubic feet per second; (ft³/s)/mi², cubic feet per second per square mile; in., inch]

Station number	Station on Mad River	Period analyzed (water years)	Median of the annual mean base flow			Median percentage of annual total streamflow due to base flow
			In.	ft³/s	$\frac{ft^3}{mi^2s}$	
03266500	At Zanesfield	1947-79	8.64	4.65	0.64	61.8
03267000	Near Urbana	1926-31 1940-92	9.05	108	.66	76.1
03267900	At St. Paris Pike	1966-92	10.1	231	.74	70.9
03269500	Near Springfield	1915-92	9.26	334	.68	68.3
03270000	Near Dayton	1916-21 1925-92	9.07	424	.67	67.2

Estimation of Sustained Ground-Water-Discharge Threshold

Estimates of an upper limit (or threshold) at which base flow can be considered to be composed predominately of sustained ground-water discharge were made by constructing and analyzing flow-duration curves prepared from the daily mean base flow estimates. Before developing the duration curves, an analysis was done to assess the influence of climatic conditions during the analysis period on the computed duration characteristics.

Effects of Analysis-Period Climatic Conditions on Flow-Duration Characteristics

Analysis of streamflow or base-flow data from a wet period generally will result (at least for higher durations) in a larger discharge value for a given percent duration than a more characteristic period would yield. Conversely, analysis of data from a dry period produces the opposite result.

The time periods analyzed for streamflow-gaging stations at Zanesfield and St. Paris Pike were significantly shorter than those of the other stations

used in this analysis. The climatic representativeness of these shorter analysis periods with respect to the longer analysis periods of the other stations was assessed by (1) computing the departures of the annual-mean streamflows for the Mad River near Springfield (the station with the longest analysis period) from the mean of the annual-mean streamflows determined for its analysis period (1915-92[1]; the reference period), and (2) computing the median and mean of the departures (at the Springfield gaging station) for the shorter analysis periods. Figure 2 shows the annual departures for the reference period at the Springfield gaging station.

The median and mean departure at the Springfield streamflow-gaging station for the period 1947-79 (the analysis period for the Zanesfield gaging station) are -2.8 and 0.7 percent, respectively, of the mean annual-mean discharge. This suggests that streamflow characteristics for the 1947-79 period are, for the purposes of this analysis, representative of the reference period.

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[1] Unless otherwise designated, time periods referred to in this report are in water years.
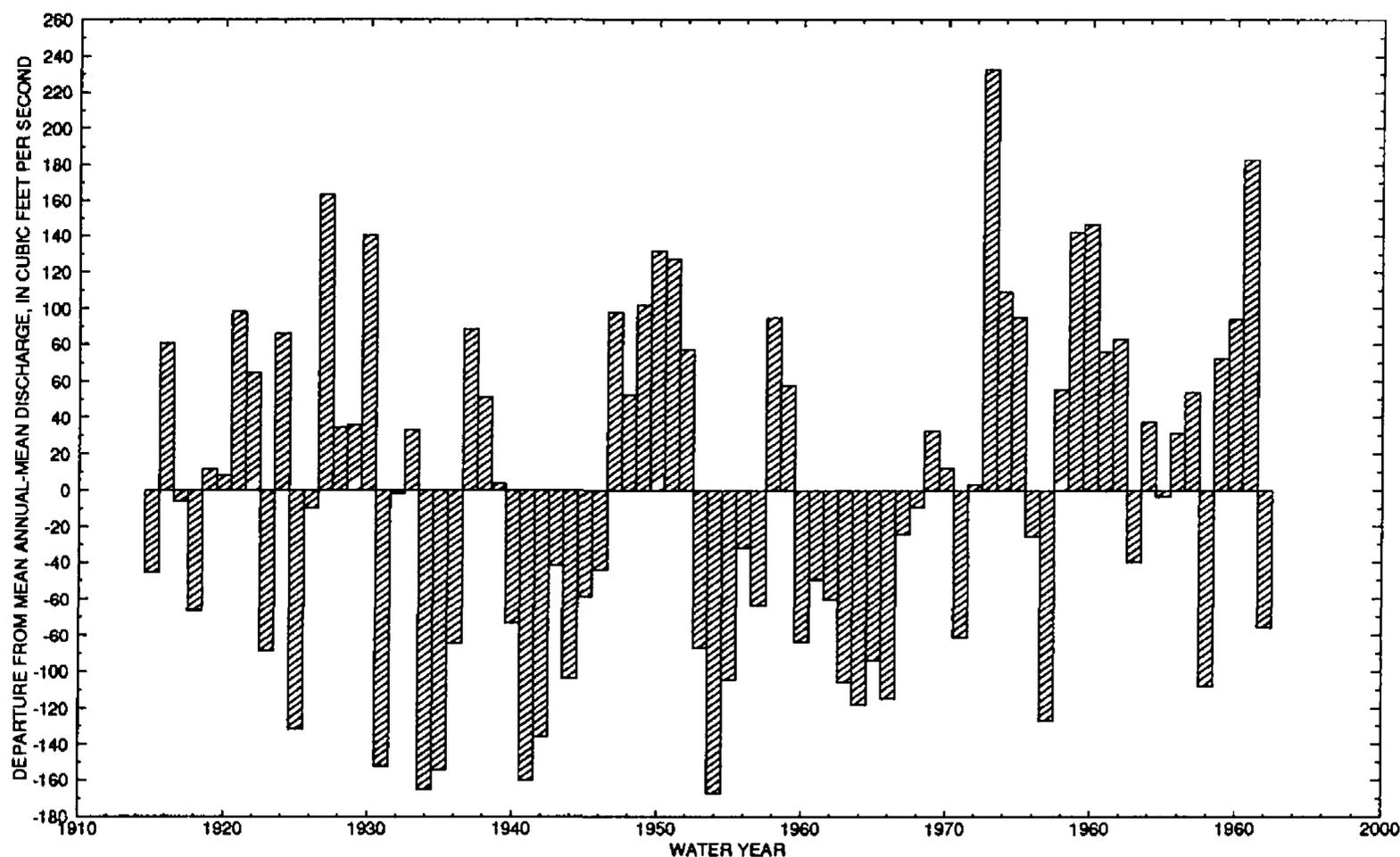
Figure 2. Annual departure from mean annual-mean discharge for water years 1915-92 at the Mad River near Springfield, Ohio .

The median and mean departure at the Springfield gaging station for the period 1966-92 (the analysis period for the St. Paris Pike gaging station) is 9.8 and 9.5 percent, respectively. This suggests that the 1966-92 period is somewhat wetter than the reference period.

Determination of Flow-Duration Characteristics

Flow-duration curves were prepared using methods described by Searcy (1959) as implemented in the USGS program DVSTAT (Dempster,1990). Because the analysis period for the St. Paris Pike gaging station was relatively wet with respect to the reference period, the duration characteristics for that site were adjusted to the reference period by means of the index-station method (Searcy, 1959). The streamflow gaging station near Springfield (03269500) was used as the index station.

Adjustments made by means of the index-station method indicate that unadjusted flow duration characteristics determined for the 1966-92 period are likely to exceed duration characteristics for the reference period by approximately 15 and 30 percent at the 80 and 95 percent durations, respectively.

Plots of streamflow and base-flow duration curves for the five Mad River streamflow-gaging stations are shown in figures 3-7 and selected streamflow and base-flow duration characteristics are listed in tables 3 and 4. The streamflow and base-flow duration curves generally do not converge (within the limits of the plot) because of a shift in the quantiles of base flow relative to streamflow. This shift is caused by the occasional presence of a surface-runoff component in some very low streamflows. If, for a given site, the class intervals used for streamflow duration analysis differ from those used for the base-flow duration analysis (as they were in this study), then (1) the duration curves may appear to converge, or (2) the gap between the duration curves may be accentuated.
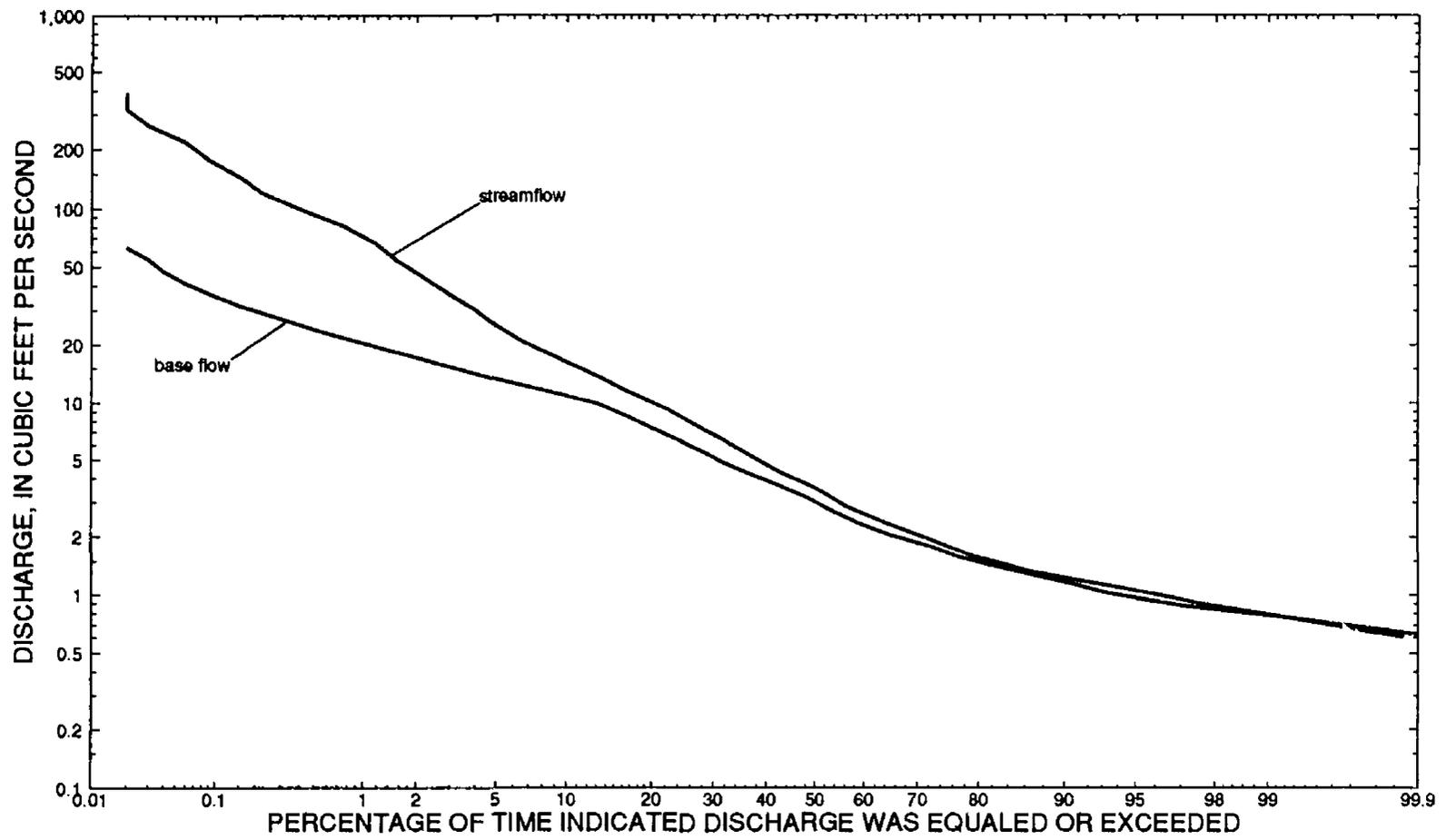
**Figure 3.** Streamflow and base-flow duration curves for the Mad River at Zanesfield, Ohio.
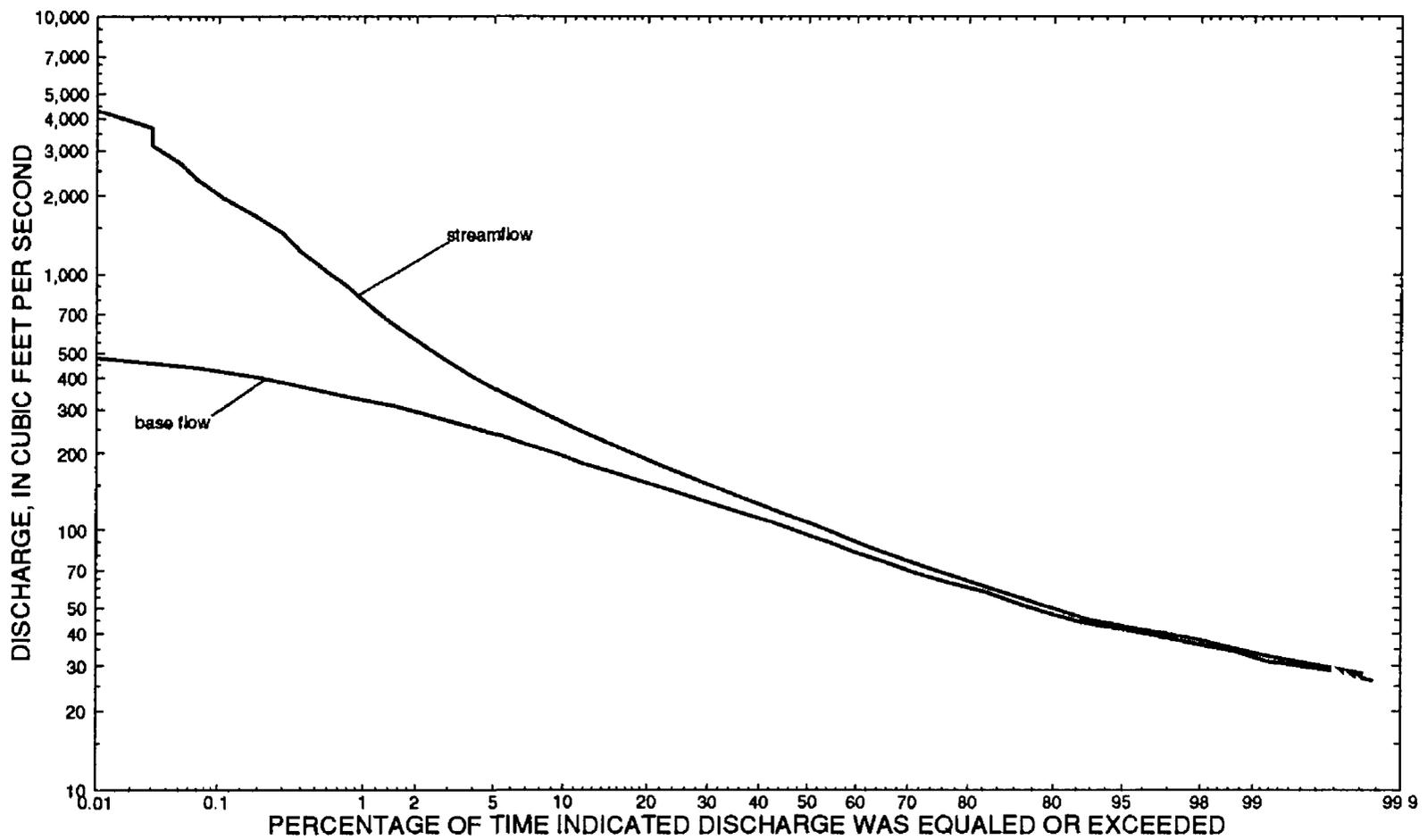

Figure 4. Streamflow and base-flow duration curves for the Mad River near Urbana, Ohio.
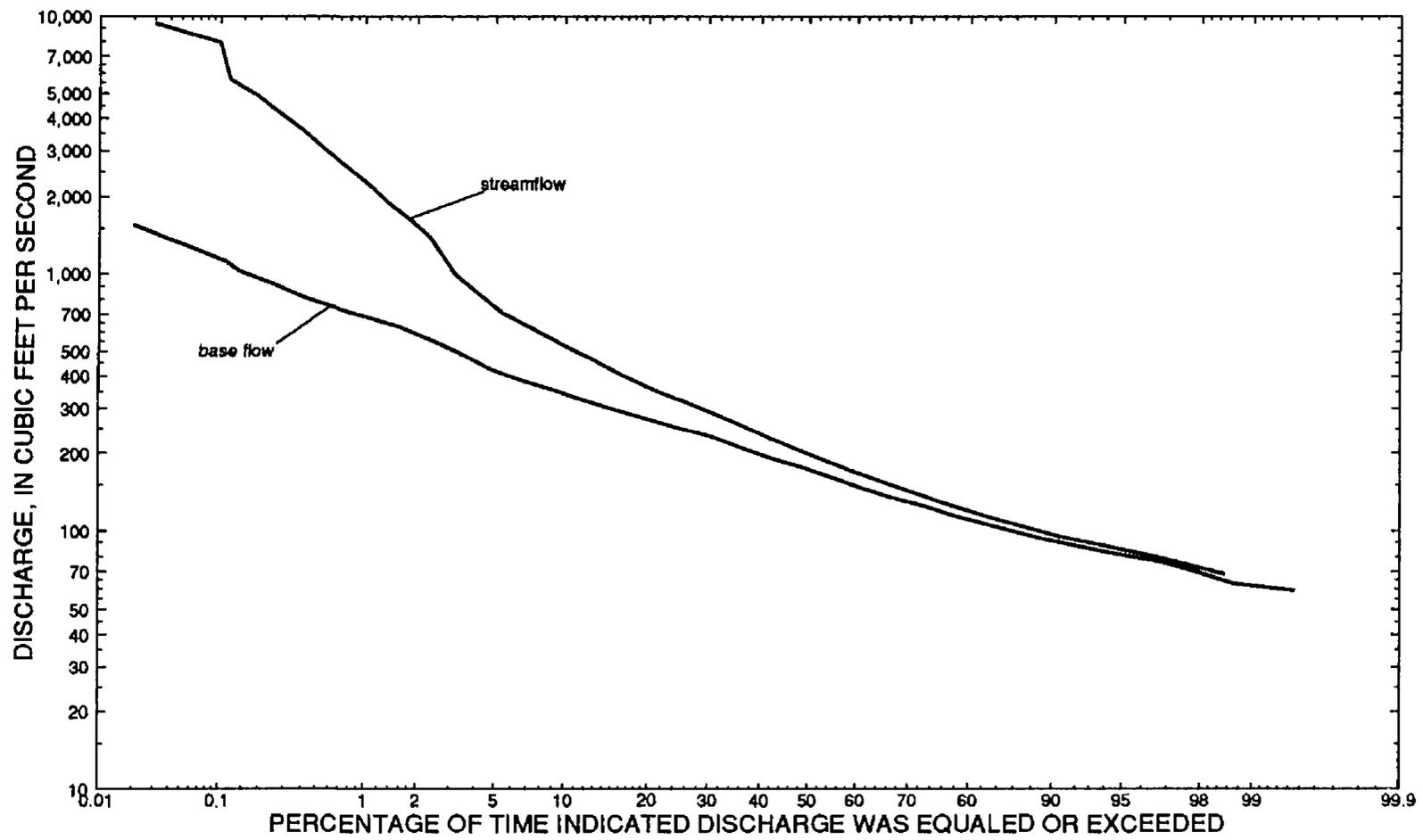
Figure 5. Streamflow and base-flow duration curves for the Mad River at St. Paris Pike (at Eagle City), Ohio.
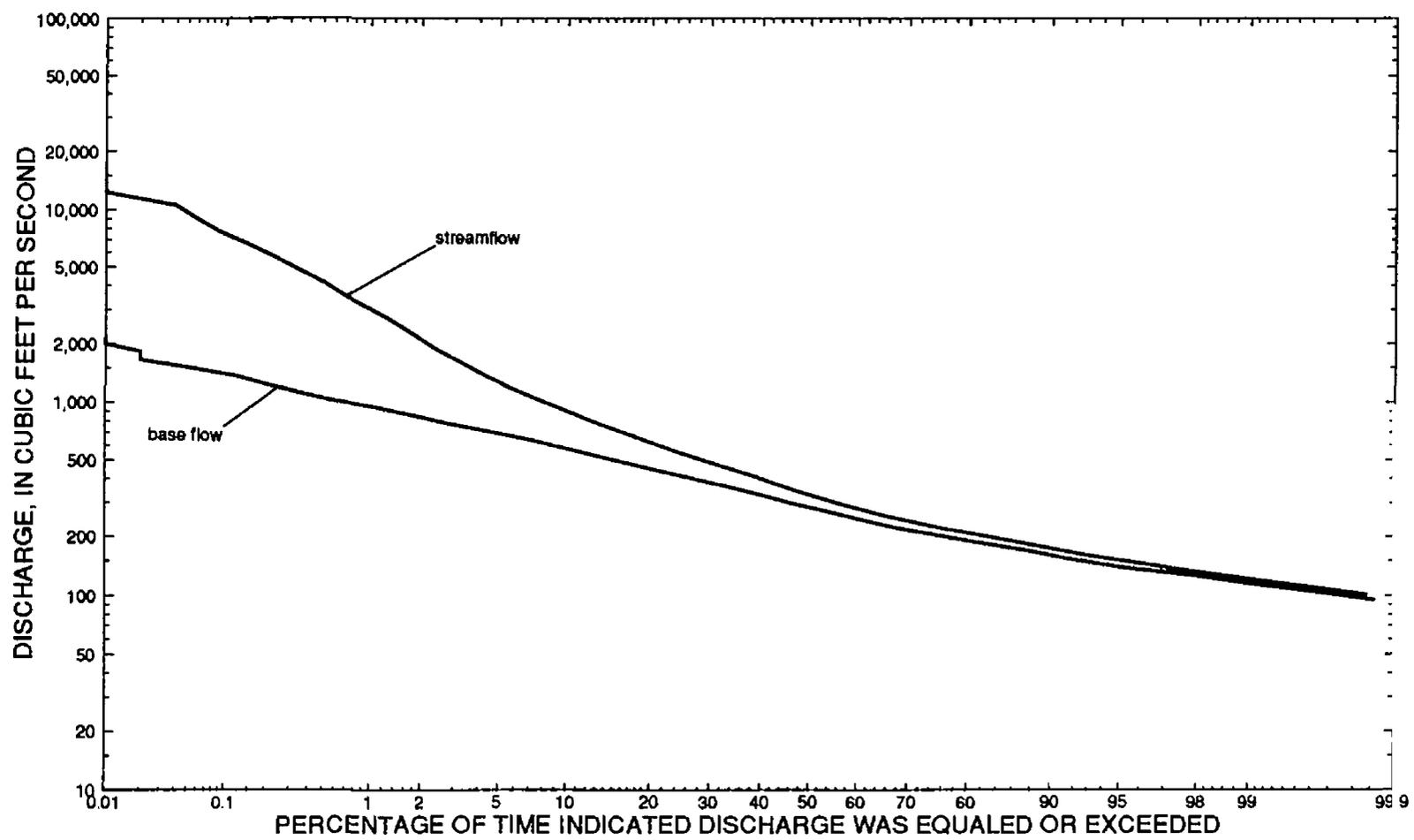
Figure 6. Streamflow and base-flow duration curves for the Mad River near Springfield, Ohio.
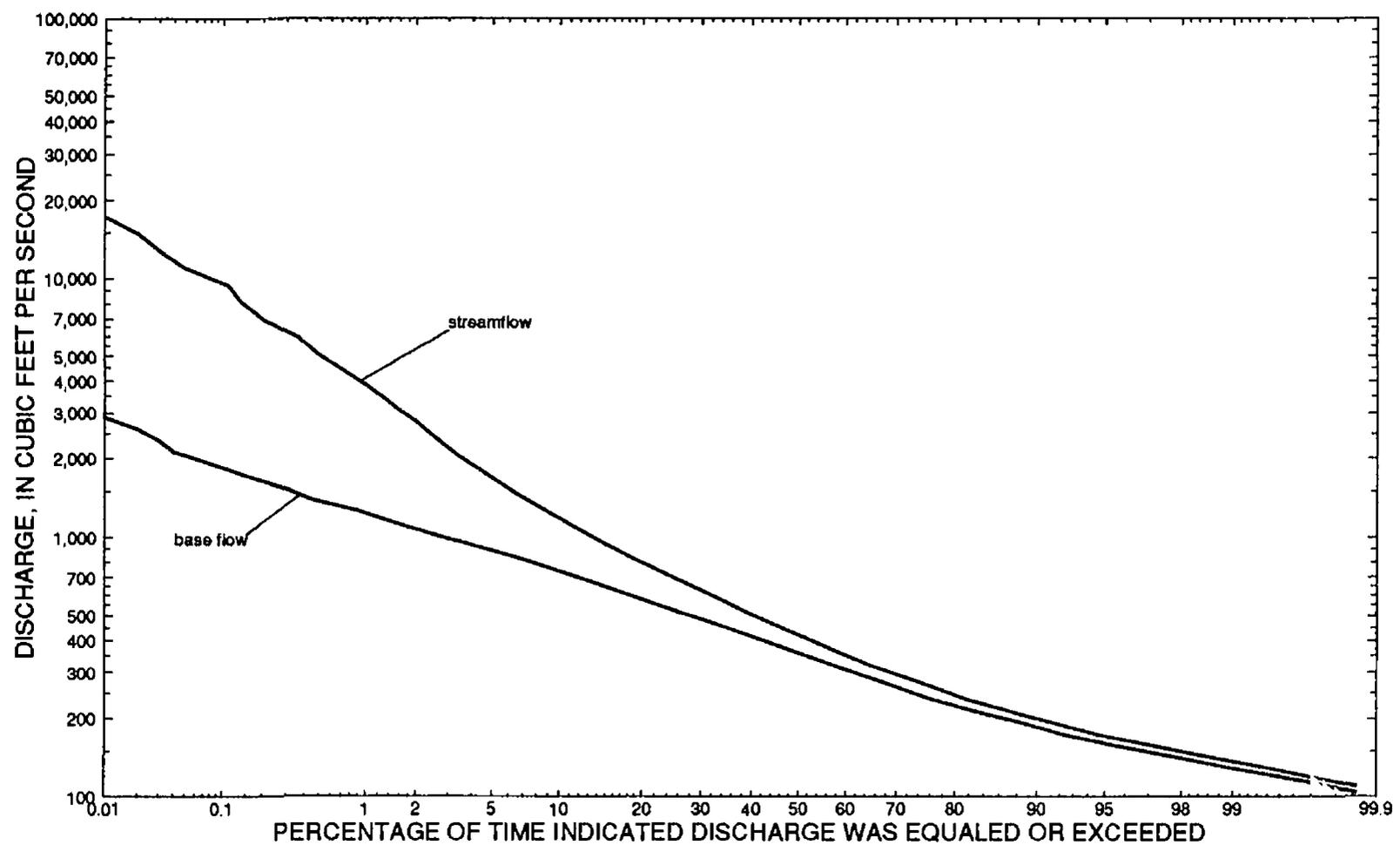
Figure 7. Streamflow and base-flow duration curves for the Mad River near Dayton, Ohio.

Table 3. Daily streamflow duration characteristics for streamflow-gaging stations on the Mad River, Ohio

[ft³/s, cubic feet per second]

Station number	Discharge (ft³/s) that was equaled or exceeded for indicated percentage of time											
	95	**90**	**85**	**80**	**75**	**70**	**60**	**50**	**40**	**30**	**20**	**10**
03266500	1.0	1.2	1.4	1.6	1.8	2.0	2.6	3.6	4.8	6.8	10	16
03267000	43	51	58	64	70	77	91	110	130	150	190	270
03267900[a]	87	97	110	120	130	140	170	210	250	300	360	530
03269500	150	170	190	210	220	240	280	330	400	490	620	910
03270000	170	200	220	250	270	300	350	420	510	630	810	1200

[a]Duration characteristics adjusted by means of index-station method using station 03269500

Table 4. Daily base-flow duration characteristics for streamflow-gaging stations on the Mad River, Ohio

[ft³/s, cubic feet per second]

Station number	Discharge (ft³/s) that was equaled or exceeded for indicated percentage of time											
	95	90	85	80	75	70	60	50	40	30	20	10
03266500	1.0	1.2	1.3	1.5	1.6	1.9	2.3	3.0	3.9	5.1	7.4	11
03267000	42	48	55	61	66	71	83	96	110	130	150	190
03267900[a]	78	88	100	110	120	130	150	180	200	230	270	340
03269500	140	160	180	190	200	220	250	280	330	380	450	580
03270000	160	190	210	230	240	270	310	360	420	490	580	740

[a]Duration characteristics adjusted by means of index-station method using station 03269500

Table 5. Statistics of sustained ground-water discharges for streamflow-gaging stations on the Mad River, Ohio

[ft³/s, cubic feet per second; (ft³/s)/mi², cubic feet per second per square mile]

Station number	Number of observa-tions	Maximum		Minimum		Mean		Median		
		ft³/s	$\frac{ft^3}{mi^2s}$	ft³/s	$\frac{ft^3}{mi^2s}$	ft³/s	$\frac{ft^3}{mi^2s}$	ft³/s	$\frac{ft^3}{mi^2s}$	percentage of median annual-mean base flow
03266500	471	0.9	0.12	0.5	0.07	0.8	0.11	0.8	0.11	17.2
03267000	1638	44	.27	24	.15	39	.24	40	.25	37.1
03267900	251	93	.30	60	.19	82	.26	82	.26	35.6
03269500	1427	140	.29	86	.18	125	.26	129	.26	38.6
03270000	2146	175	.28	94	.15	152	.24	155	.24	36.6

Selection of the Sustained Ground-Water-Discharge Threshold

Eberts (in press) suggests that the population of daily mean base flows that form the upper limb of the base-flow-duration curve is composed of an appreciable amount of discharge from local ground-water-flow systems whereas the lower limb population is composed predominately of discharge from deep, stable regional and possibly intermediate ground-water flow systems. Consequently, the point on the base-flow-duration curve where the relatively flat slope of the lower limb changes to the steeper slope of the upper limb was assumed to be the sustained ground-water-discharge threshold (fig. 8). The sustained ground-water-discharge thresholds, determined visually from the base-flow duration curves, are reported in table 1. The range of sustained ground-water-discharge
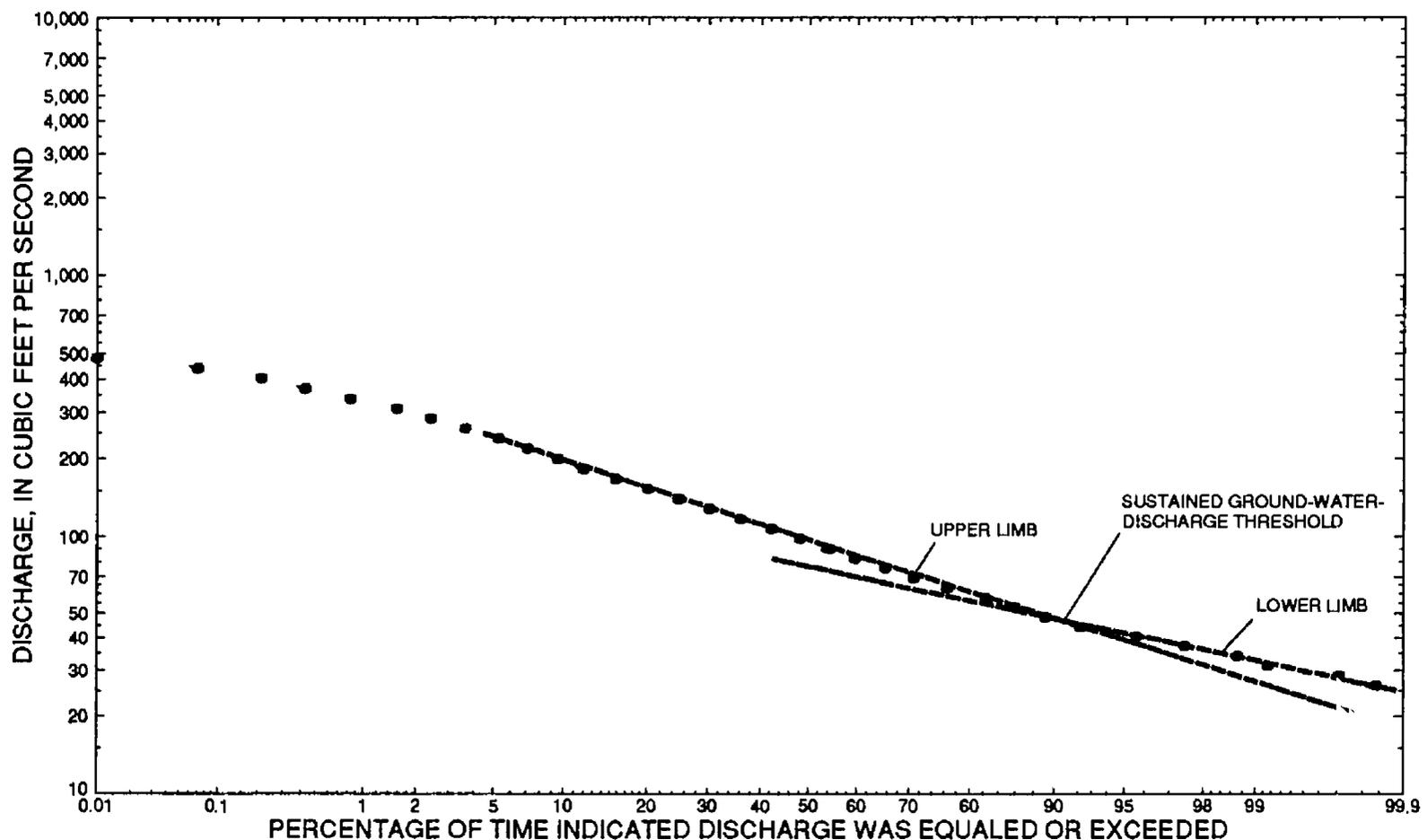
Figure 8. Base-flow duration curve showing selection of sustained ground-water-discharge threshold.

thresholds reported in table 1 corresponds to a range in daily streamflow duration of about 91 to 98 percent.

Statistics of Sustained Ground-Water Discharge

The daily mean base-flow time series were filtered to remove values larger than the estimated sustained ground-water-discharge threshold. Those values that passed the filter are considered to be composed predominately of sustained ground-water discharge. Summary statistics of the sustained ground-water-discharge values were determined and are reported in table 5. The median sustained ground-water discharge ranged from 0.11 (ft^3/s)/mi^2 at Zanesfield to 0.26 (ft^3/s)/mi^2 at St. Paris Pike (at Eagle City) and near Springfield. The median sustained ground-water discharge, expressed as a percentage of the median annual-mean base flow, ranged from 17.2 percent at Zanesfield to 38.6 percent near Springfield.

Even very low streamflows can contain a surface-runoff component. Consequently, the daily mean baseflows characterized as sustained ground-water discharge were compared with same-day

streamflow values to determine the estimated percentage of sustained ground-water discharge composing the streamflow. Results of that comparison show that 79 to 92 percent of the same-day streamflow values at the five Mad River gaging stations were composed of 85 percent or greater sustained ground-water discharge. In addition, 73 to 86 percent of the same-day streamflow values were composed of 90 percent or greater sustained ground-water discharge (table 6).

Effects of Regulation on Base Flow

Regulation can affect flow characteristics significantly. While some forms of regulation can affect both high and low flows, only the effects of regulation on base flow are of concern in this study. Three of the five streamflow-gaging stations listed in table 1 are affected to some degree, by regulation.

Low flows at station 03267900 (Mad River at St. Paris Pike at Eagle City, Ohio) may be affected by pumpage from the Springfield City well field, located less than 1 mi upstream, adjacent to the Mad River. Pumpage, averaging 20.2 ft^3/s in 1992, is returned to

Table 6. Selected relations between base flows characterized as sustained ground-water discharge and streamflows occurring on the same day
[%, percent]

Station number	Station on Mad River	Mean ratio of sustained ground-water discharge to streamflow	Percentage of same-day streamflow values composed of indicated percentage of sustained ground-water discharge or greater	
			85%	90%
03266500	At Zanesfield	0.96	90	85
03267000	Near Urbana	.95	92	86
03267900	At St. Paris Pike	.91	79	73
03269500	Near Springfield	.91	83	73
03270000	Near Dayton	.91	86	77

the Mad River below the St. Paris Pike gage as treated wastewater.

Studies conducted by Schalk (1992) and R.A. Sheets (U.S. Geological Survey, written commun., 1994) suggest that the City of Dayton's Rohrers' Island well field may affect low flows at station 03270000 (Mad River near Dayton, Ohio). Pumpage from the Rohrers' Island well field averaged 59.6 ft³/s in 1992.

The C.J. Brown Reservoir, completed on Buck Creek in 1972, provides some regulation of streamflow on the Mad River from the confluence with Buck Creek (3.1 miles downstream from the gage at St. Paris Pike at Eagle City, Ohio) to the mouth.

A double-mass analysis was done to assess whether the potential sources of regulation listed above appreciably affected base flows. Double-mass curves were prepared to compare cumulative base flow at the unregulated Urbana gage with cumulative base flow at the St. Paris Pike, Springfield, and Dayton gages. If appreciable change in regulation affecting base flow had occurred over time, the double-mass curves would reflect that change by changing slope. None of the double-mass curves deviated appreciably from a straight line, suggesting that (1) base-flow regulation resulting from pumpage from the Springfield and

Dayton City well fields is either negligible or has remained fairly constant over the analysis period, and (2) the affect of regulation on base flow, resulting from installation and operation of the C.J. Brown Reservoir, is negligible in the Mad River.

SUMMARY AND CONCLUSIONS

The hydrograph-separation computer program HYSEP was used to estimate daily and annual-mean base flows for five streamflow-gaging stations on the Mad River. Hydrograph separation was done by means of the local-minimum method because it provided the lowest (most conservative) base-flow estimates of the methods implemented in HYSEP. The median of the annual mean base flows for the five Mad River gaging stations ranged from 0.64 to 0.74 (ft³/s)/mi². The median percent of annual total streamflow attributed to base flow ranged from 61.8 to 76.1 percent.

Flow-duration curves prepared from the daily mean base flows were used to estimate an upper limit, or threshold, at which base flow can be considered to be composed predominately of sustained ground-water discharge. The analysis period for the St. Paris Pike, at Eagle City streamflow-gaging station was found to be

wet relative to the 1915-92 reference period. Streamflow and base-flow duration characteristics for the St. Paris Pike station were adjusted to the reference period by means of the index-station method.

The point on the base-flow-duration curve where the relatively flat slope of the lower limb changes to the steeper slope of the upper limb was assumed to be the sustained ground-water-discharge threshold. The sustained ground-water-discharge thresholds ranged from 0.9 to 175 ft^3/s for the five Mad River streamflow-gaging stations.

The estimated base-flow time series for each of the five Mad River gaging stations were filtered to remove values that exceeded their respective sustained ground-water-discharge thresholds. Values that passed the filter were compared with same-day streamflows to determine the estimated percentage of sustained ground-water discharge composing the streamflow. This comparison showed that 79 to 92 percent of same-day streamflows were composed of at least 85 percent sustained ground-water discharge, and 73 to 86 percent of same-day streamflows were composed of at least 90 percent sustained ground-water discharge.

Summary statistics were determined for the sustained ground-water-discharge values. The median (and mean) of the sustained ground-water-discharge values ranged from 0.11 to 0.26 $(ft^3$/s$)$/mi^2 for the five Mad River gaging stations.

A double-mass analysis was done to assess whether potential regulation by the Springfield and Dayton City well fields and the C.J. Brown Reservoir appreciably affected base flows. This analysis indicated that (1) base flow regulation resulting from pumpage from the Springfield and Dayton City well fields is either negligible or has remained fairly constant over the analysis period, and (2) the affect of regulation on base flow resulting from the installation of the C.J. Brown Reservoir is negligible in the Mad River.

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