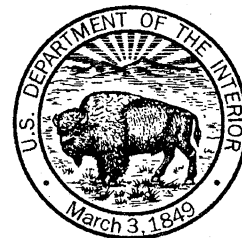


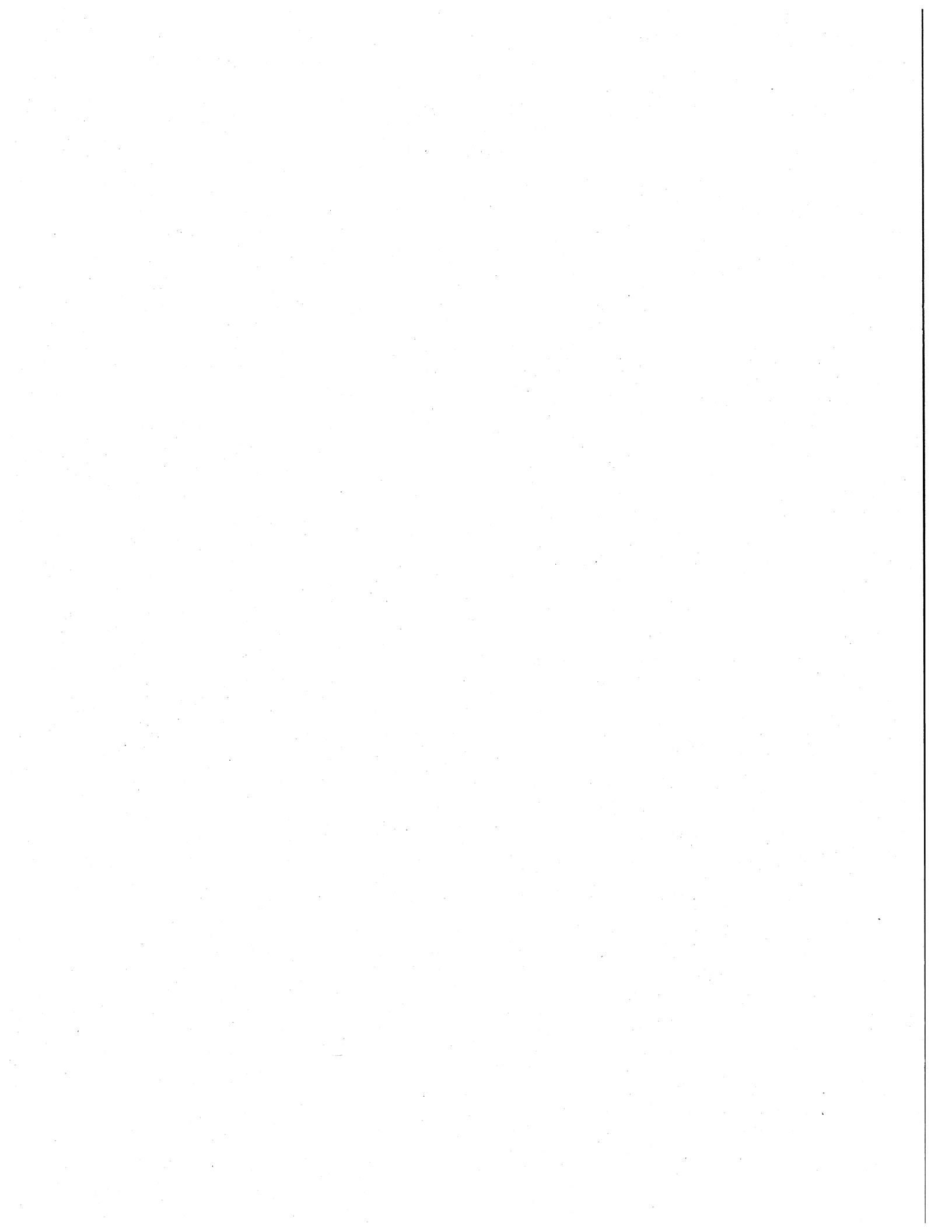
REGIONALIZATION OF LOW-FLOW CHARACTERISTICS OF ARKANSAS STREAMS

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 93-4013

Prepared in cooperation with the
ARKANSAS SOIL AND WATER CONSERVATION COMMISSION





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By A.H. Ludwig and Gary D. Tasker

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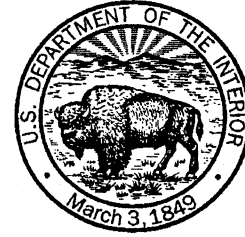
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Little Rock, Arkansas
1993

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS

<u>Multiply</u>	<u>By</u>	<u>To obtain</u>
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second
mile (mi)	1.609	kilometer
square mile (mi ²)	2.590	square kilometer

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ABSTRACT

Equations for estimating the 7-day 2-year and 7-day 10-year low flow at sites on ungaged streams are presented. Regression analysis was used to develop equations relating basin characteristics and low-flow characteristics at 58 continuous-record gaging stations and 151 partial-record sites. Significant basin characteristics in the equations are drainage area and percentage of drainage basin underlain by permeable bedrock units. The study area, which encompasses the western two-thirds of the State, is divided into three regions based on the similarity of basin characteristics within each region. The analysis includes records for only those stations that are not highly regulated and have drainage areas less than 1,000 square miles.

A three-step method is used to estimate low-flow characteristics at ungaged sites. The first step involves the use of a logistic regression to determine the probability that the 7-day annual minimum flow is zero at the site of interest. The second step uses this estimated probability of 7-day annual zero flow to determine if the estimated value of the 7-day 2-year or the 7-day 10-year low flow is zero or needs to be estimated from one of the regional equations, which are based on a generalized-least-squares model for sites with non-zero flow. The third step involves the use of the regional equation, if flow is indicated, to determine the 7-day 2-year and 10-year low-flow values.

Computer software has been written to facilitate the computation of low-flow characteristics at sites of interest. The software is provided in written form and on a disk.

INTRODUCTION

Knowledge of low-flow characteristics of Arkansas streams is important in water-resource planning, particularly when questions related to draft storage requirements, dilution of contaminants, navigation, and maintenance of fish and wildlife habitat are concerned. From data collected at continuous and partial-record gaging stations operated by the U.S. Geological Survey (USGS) and other Federal agencies, low-flow characteristics (for example, 7-day 2-year and 7-day 10-year low flows) have been computed (Ludwig, 1992) and are available for helping make water-resource management decisions at these sites. Low-flow characteristics are commonly needed at sites for which daily discharge records or miscellaneous discharge measurements do not exist. This report, a product of a study by the USGS, in cooperation with the Arkansas Soil and Water Conservation Commission, is the first to describe a method for the determination of low-flow characteristics at ungaged sites within the State of Arkansas.

Purpose and Scope

This report briefly describes the regression analysis techniques selected to effect the transfer of low-flow characteristics from gaged to ungaged stream sites, and provides the resulting predictive equations to estimate values of 7-day low flow for recurrence intervals of 2 and 10 years ($Q_{7,2}$ and $Q_{7,10}$) at ungaged stream sites in the study area.

The study area includes the western two-thirds of the State (fig. 1). The eastern one-third of the State, which lies within the Mississippi Alluvial Plain, has been excluded from the study because withdrawals and return flows associated with irrigation throughout the area make the determination of predictable low-flow characteristics impossible.

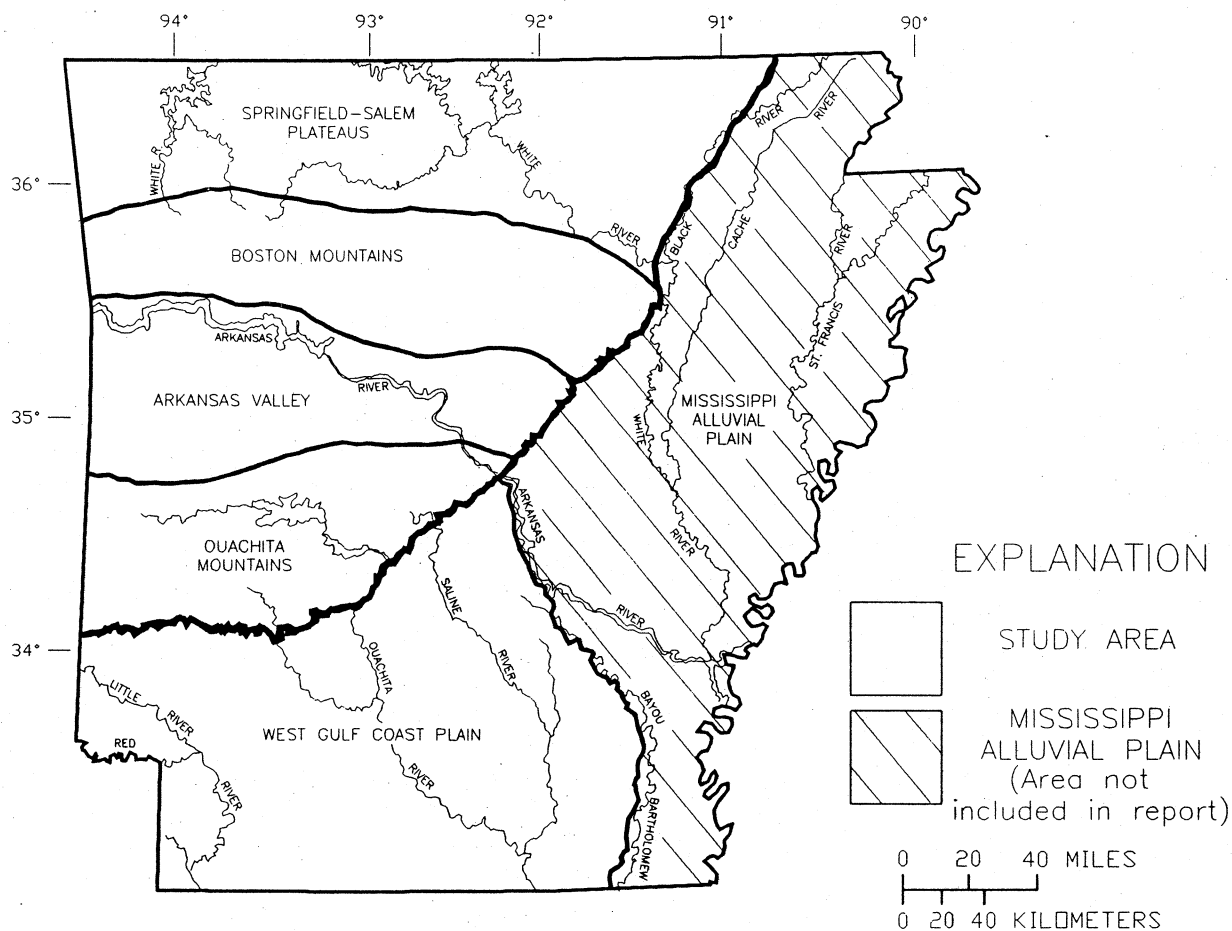


Figure 1.--Location of study area and physiographic divisions.

Previous Investigations

Four previous reports deal with statewide low-flow stream characteristics. The first report by Hines (1965) contained information on low-flow frequency and flow duration for unregulated sites. The second report (Hines, 1975) contained updated low-flow statistical information for regulated as well as unregulated sites. Hunrichs (1983) identified perennial streams in most areas of Arkansas based on a range of 7-day 10-year low-flow ($Q_{7,10}$) discharges. The fourth report (Ludwig, 1992) is an update, based on additional period of record (1970-1990), of the information contained in the second report by Hines (1975).

This report is the first that has dealt with the regionalization of low-flow characteristics for Arkansas streams. The low-flow characteristics for gaged sites on Arkansas streams presented by Ludwig (1992) are the basis for the regionalization work documented in this report.

Techniques for determining the storage requirements of Arkansas streams are described in a report by Patterson (1968). Another report by Patterson (1971) contains information on the magnitude and frequency of floods in Arkansas through 1968. This work has also been updated through 1984 in a report by Neely (1987). These and other reports describing streamflow characteristics in Arkansas are listed in the references at the end of the report.

LOW-FLOW DATA

The study is based on the analysis of daily discharge records from 58 continuous-record gaging stations, including 23 active and 35 discontinued stations, and from 151 partial-record sites. These data have been updated through the 1990 water year (Ludwig, 1992). Only those continuous-record gaging stations that have 10 or more years of streamflow record, that are not highly regulated, and have drainage areas less than 1,000 mi² were included in the analysis. Partial-record sites were limited to locations having six or more low-flow measurements.

Table 1 contains the list of stations and associated data upon which the regionalization analysis presented in this report is based. Included in table 1 are the values for $Q_{7,2}$ and $Q_{7,10}$ that have been determined at each site (Ludwig, 1992). Also included are the region and basin factor for each station. Region is a designation for a geographic area in which low flows may be estimated by a common equation. Regions are primarily defined on the basis of the permeability of the underlying bedrock. Basin factor defines the percentage of a given drainage basin underlain by permeable bedrock. The approximate location and type of each station is shown in plate 1. The map number given in table 1 is the station reference number in plate 1.

METHODOLOGY FOR REGIONALIZING LOW-FLOW CHARACTERISTICS

Two types of regression analysis were used in this study to regionalize low-flow characteristics based upon data observed at stream-gaging stations. Logistic regression was used to estimate the probability of an annual minimum flow being zero and generalized least squares regression was used to estimate $Q_{7,2}$ and $Q_{7,10}$. The independent variables in both models are basin characteristics. The theory behind each approach is discussed in the following two sections.

Logistic Regression to Estimate Probability of Zero Flow

At many streams in Arkansas the minimum flow for a year is zero. To estimate the probability of having a minimum of zero at an ungaged site, a regional logistic regression model that relates probability of a zero minimum flow at a site to physical, meteorological, and geological characteristics of the watershed can be developed (Tasker, 1989). Consider a collection of p basin characteristics denoted by the vector $x' = (x_1, x_2, \dots, x_p)$. Let $\pi(x)$ denote the probability that the annual minimum flow associated with a duration, such as 7-day, 30-day, or 90-day, is nonzero. The multiple logistic regression model may be described as follows:

$$\pi(x) = \frac{e^{g(x)}}{1 + e^{g(x)}}$$

where

$$g(x) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_p x_p.$$

Consequently, the probability that the annual minimum flow associated with a particular time duration is zero may be described as follows:

$$1 - \pi(x) = 1 - \frac{e^{g(x)}}{1 + e^{g(x)}}$$

By use of sample data collected at stream gages in the area (table 1), the unknown β 's are estimated by maximizing the log likelihood function

$$L(\beta) = \sum_{i=1}^n \{ y_i \ln [\pi(x)] + (1 - y_i) \ln [1 - \pi(x)] \}$$

in which $y_i = 1$ if an observed annual minimum is nonzero in year i and $y_i = 0$ if an observed annual minimum is zero and n is the total number of observations at all sites.

Table 1.--Hydrologic characteristics for surface-water gaging stations used in the regression analyses--Continued

Map number	Station name	Station number	Region	Drainage area (mi ²)	Basin factor (percent)	7-day 2-year low flow (ft ³ /s)	7-day 10-year low flow (ft ³ /s)
48	Saline River near Dierks	7341000	3	121	10	0.4	0
49	Bodcau Creek at Stamps	7349430	2	236	0	<.1	0
50	South Fork Ouachita River at Mt. Ida	7356500	3	61.0	100	2.6	0.1
51	Caddo River at Alpine	7359800	3	301	75	27	13
52	Little Missouri River at Narrows Dam near Murfreesboro	7360501	3	239	45	12	5.1
53	Little Missouri River near Murfreesboro	7361000	3	383	35	22	9.6
54	Ozan Creek near McCaskill	7361200	3	144	0	0	0
55	Moro Creek near Fordyce	7362500	2	240	0	0	0
56	Saline River at Benton	7363000	3	550	40	21	2.3
57	Cornie Bayou near Three Creeks	7365800	2	180	0	.2	0
58	Three Creeks near Three Creeks	7365900	2	50.4	0	.2	0

PARTIAL-RECORD SITES

59	White River at Combs	7047976	1	90.3	0	0.1	0
60	White River at Elkins	7047980	1	184	0	.9	0.1
61	Middle Fork White River near Fayetteville	7047985	1	73.4	0	<.1	0
62	Richland Creek at Goshen	7048800	1	138	50	1.4	<.1
63	War Eagle Creek near Huntsville	7048960	1	105	20	.8	.2
64	Kings River near Kingston	7050225	1	98.0	15	1.5	.3
65	Warm Fork Creek at Rockhouse	7050230	1	19.1	100	0	0
66	Kings River near Pleasant Valley	7050250	1	346	100	2.6	.2
67	Osage Creek at Osage	7050285	1	46.7	20	0	0
68	Osage Creek southwest of Berryville	7050390	1	139	80	.8	.1
69	Long Creek at Alpina	7053200	1	67.2	20	.8	.1
70	Yocum Creek near Oak Grove	7053250	1	52.8	90	4.0	2.9
71	Bear Creek near Omaha	7054410	1	133	95	2.8	1.7

Table 1.--Hydrologic characteristics for surface-water gaging stations used in the regression analyses--Continued

Map number	Station name	Station number	Region	Drainage area (mi ²)	Basin factor (percent)	7-day 2-year low flow (ft ³ /s)	7-day 10-year low flow (ft ³ /s)
72	West Sugarloaf Creek near Lead Hill	7054420	1	31.9	100	1.8	0.3
73	Crooked Creek at Pyatt	7055600	1	207	95	14	6.5
74	Crooked Creek at Yellville	7055608	1	406	100	.2	0
75	Buffalo River at Pruitt	7055680	1	190	65	4.4	1.0
76	Little Buffalo River at Jasper	7055700	1	126	25	2.4	.3
77	Bear Creek near Marshall	7056510	1	64.3	25	4.2	2.0
78	Big Creek near Big Flat	7057100	1	91.6	75	5.0	2.2
79	Piney Creek near Calico Rock	7060520	1	78.3	100	8.4	6.3
80	Hughes Creek near Mountain View	7060670	1	3.20	10	0	0
81	South Sylamore Creek at Allison	7060700	1	143	80	8.0	5.9
82	North Sylamore Creek near Allison	7060720	1	68	100	3.0	1.4
83	Polk Bayou at Batesville	7060900	1	168	100	34	26
84	Little Black River at Success	7068600	1	385	100	38	26
85	Mud Creek near Ingram	7068880	1	34.2	100	.7	.3
86	Fourche River above Pocahontas	7068890	1	229	100	12	6.3
87	Fourche River near Pocahontas	7068900	1	304	100	14	8.5
88	Myatt Creek near Salem	7069265	1	101	100	2.4	1.7
89	Spring River near Hardy	7069266	1	540	100	250	190
90	South Fork Spring River near Salem	7069270	1	170	100	10	7.5
91	South Fork Spring River near Hardy	7069300	1	324	100	55	41
92	Martins Creek near Williford	7069350	1	66.9	100	4.2	3.0
93	Janes Creek at Ravenden Springs	7069400	1	79.3	100	1.2	.6
94	Strawberry River near Franklin	7072900	1	155	100	3.2	1.7
95	Mill Creek at Evening Shade	7073600	1	12.2	100	14	12
96	North Big Creek near Evening Shade	7073995	1	74.8	100	8.5	6.3
97	South Big Creek near Strawberry	7074248	1	69.4	100	20	13
98	Reeds Creek near Strawberry	7074250	1	34.9	100	12	9.5
99	Cooper Creek near Smithville	7074260	1	31.9	100	6.8	5.4

Table 1.--Hydrologic characteristics for surface-water gaging stations used in the regression analyses--Continued

Map number	Station name	Station number	Region	Drainage area (mi ²)	Basin factor (percent)	7-day 2-year low flow (ft ³ /s)	7-day 10-year low flow (ft ³ /s)
100	Curia Creek near Dowdy	7074400	1	55.6	100	5.4	4.1
101	Dota Creek near Newark	7074450	1	56.6	20	4.0	3.0
102	Departee Creek near Coffeerville	7074800	1	101	0	<.1	<.1
103	Middle Fork Little Red River at Leslie	7074890	2	71.8	0	0	0
104	Devils Fork Little Red River near Brownsville	7075200	2	209	0	.2	0
105	Archey Creek at Clinton	7075390	2	118	0	.3	0
106	Big Creek near Pangburn	7076510	2	51.4	0	.2	0
107	Big Creek near Letona	7076530	2	72.6	0	.3	0
108	Bayou Des Arc near Garner	7076800	2	96.7	0	<.1	0
109	Bull Creek near McRae	7076880	2	95.8	0	0	0
110	McKisic Creek near Bella Vista	7188810	2	22.2	100	4.5	1.3
111	Muddy Fork Illinois River near Savoy	7194790	1	73.5	15	1.5	.3
112	Illinois River at Savoy	7194800	1	167	40	3.5	1.2
113	Little Osage Creek near Healing Springs	7194950	1	46.8	100	14	6.5
114	Illinois River near Siloam Springs	7195400	1	509	100	65	18
115	Evansville Creek at Evansville	7196950	1	24.4	0	.1	<.1
116	Jones Creek near Waldron	7246970	2	70.6	0	<.1	0
117	Poteau River near Bates	7247010	2	251	0	.3	0
118	Black Fork near Page, Okla.	7247100	2	46.6	0	.1	0
119	Big Creek at Howard	7247200	2	11.1	0	<.1	0
120	Haws Creek near Black Fork	7247300	2	10.5	0	<.1	0
121	Lee Creek at Natural Dam	7249600	2	168	0	.3	0
122	Mountain Fork Creek at Natural Dam	7249700	2	38.9	0	<.1	0
123	Lee Creek near Short, Okla.	7249800	2	236	0	.4	0
124	Little Lee Creek near Short, Okla.	7249900	2	103	0	<.1	0
125	Vache Grasse Creek near Lavaca	7250600	2	105	0	<.1	0
126	Big Creek at Bloomer	7250700	2	53.1	0	0	0
127	Cedar Creek near Rudy	7251400	2	51.5	0	<.1	0

Table 1.--Hydrologic characteristics for surface-water gaging stations used in the regression analyses--Continued

Map number	Station name	Station number	Region	Drainage area (mi ²)	Basin factor (percent)	7-day 2-year low flow (ft ³ /s)	7-day 10-year low flow (ft ³ /s)
128	Little Mulberry Creek near Oark	7251800	2	66.3	0	0.2	0
129	Mulberry River near Cass	7251900	2	266	0	.8	0
130	Little Mulberry Creek near Mulberry	7252100	2	49.7	0	<.1	0
131	White Oak Creek near Ozark	7252300	2	75.0	0	.1	0
132	Horsehead Creek at Hartman	7256200	2	127	0	.2	0
133	Big Shoal Creek near New Blaine	7256700	2	50.0	0	<.1	0
134	Little Piney Creek near Lamar	7257200	2	154	0	.5	0
135	Middle Fork Illinois Bayou near Hector	7257470	2	57.3	0	.3	0
136	North Fork Illinois Bayou near Scottsville	7257480	2	87.4	0	.5	0
137	Sugar Creek near Sugar Grove	7258700	2	95.0	0	<.1	0
138	West Fork Point Remove Creek near Hattieville	7260673	2	222	0	.6	0
139	Point Remove Creek near Morrilton	7260700	2	488	0	1.0	0
140	East Fork Cadron Creek near Enola	7261200	2	122	0	.6	0
141	Mill Creek near Boles	7261400	2	50.5	0	<.1	0
142	Fourche LaFave River at Boles	7261420	2	176	0	.2	0
143	Gafford Creek near Bluffton	7261600	2	41.0	0	<.1	0
144	Maumelle River at Williams Junction	7263290	2	26.5	0	0	0
145	Fourche Creek at Little Rock	7263600	2	163	15	1.5	.6
146	Walnut Bayou near Foreman	7336900	2	90.4	0	<.1	0
147	Twomile Creek near Hatfield	7338700	3	15.9	60	.8	.3
148	Mountain Fork near Hatfield	7338720	3	168	15	1.3	.2
149	Rolling Fork near Grammis	7339200	3	51.0	40	.2	0
150	West Flat Creek near Foreman	7340200	2	10.7	0	0	0
151	Cossatot River near Umpire	7340400	3	142	30	8.6	3.4
152	Lick Creek near Wilton	7340750	2	19.3	0	0	0
153	Rock Creek near Dierks	7341100	3	9.46	0	0	0
154	Bois D'Arc near Hope	7341690	3	36.4	20	1.0	.3
155	Maniece Bayou near Canfield	7342150	2	85.2	0	.6	0

Table 1.--Hydrologic characteristics for surface-water gaging stations used in the regression analyses--Continued

Map number	Station name	Station number	Region	Drainage area (mi ²)	Basin factor (percent)	7-day 2-year low flow (ft ³ /s)	7-day 10-year low flow (ft ³ /s)
156	McKinney Bayou near Garland	7342350	2	175	0	<0.1	0
157	Bayou Dorcheat at Buckner	7348600	2	125	0	0	0
158	Wheaton Branch near Bodcaw	7349420	2	3.09	100	0	0
159	Ouachita River near Mena	7355810	3	39.6	5.0	.1	<.1
160	Big Fork tributary at Big Fork	7355900	2	.19	100	.1	<.1
161	Irons Fork near Aly	7356300	3	47.2	0	<.1	0
162	Glazypeau Creek at Mountain Pine	7357710	3	30.1	100	1.8	.1
163	Fourche A Loupe Creek near Hot Springs	7358010	3	4.37	100	.2	<.1
164	Gulpha Creek near Hot Springs	7358700	3	38.8	100	1.6	.1
165	Caddo River near Black Springs	7359590	3	14.7	100	7.0	5.8
166	Caddo River at Caddo Gap	7359600	3	125	100	22	14
167	Caddo River near Caddo Gap	7359610	3	136	100	27	16
168	L'Eau Frais Creek at Joan	7360100	3	74.2	60	3	.4
169	Cypress Creek at Manning	7360160	3	55.9	100	1.3	.1
170	Little Missouri River near Langley	7360200	3	68.4	90	10	8.0
171	Prairie Creek near Murfreesboro	7361025	3	33.7	0	.2	0
172	North Fork Ozan Creek near McCaskill	7361160	3	97.3	0	.1	0
173	Wolf Creek near Antoine	7361540	3	37.4	30	.8	0
174	Little Terre Rouge Creek near Emmet	7361640	3	40.5	20	.2	<.1
175	Terre Rouge Creek near Prescott	7361650	3	232	10	1.1	.2
176	Caney Creek near Bluff City	7361700	3	181	0	0	0
177	Terre Noire Creek near Hollywood	7361755	3	35.9	0	0	0
178	Terre Noire Creek near Gurdon	7361800	3	258	0	.5	0
179	Freeo Creek near Eagle Mills	7361900	3	78.0	20	.4	<.1
180	Two Bayou at Camden	7362060	2	118	0	<.1	0
181	Locust Bayou at Locust Bayou	7362070	2	62.3	0	0	0
182	Gum Creek near Stephens	7362080	2	26.9	0	0	0
183	Camp Creek near Smackover	7362090	2	43.3	0	.1	0

Table 1.--Hydrologic characteristics for surface-water gaging stations used in the regression analyses--Continued

Map number	Station name	Station number	Region	Drainage area (mi ²)	Basin factor (percent)	7-day 2-year low flow (ft ³ /s)	7-day 10-year low flow (ft ³ /s)
184	Champagnolle Creek at Hampton	7362300	2	69.4	0	0	0
185	Whitewater Creek near Tinsman	7362540	2	25.0	0	0	0
186	Moro Creek near Banks	7362550	2	385	0	0	0
187	Alum Fork at Crows	7362600	3	121	30	1.8	.2
188	Middle Fork at Crows	7362700	3	102	90	6.5	2.3
189	South Fork near Hot Springs	7362800	3	12.6	100	1.8	1.1
190	North Fork at Paron	7362870	3	20.2	5.0	0	0
191	North Fork near Benton	7362900	3	133	30	1.8	.1
192	Big Creek at Poyen	7363110	3	32.1	0	.6	<.1
193	Saline River near Leola	7363160	3	896	34	20	6.0
194	Lost Creek near Sheridan	7363180	2	68.0	0	0	0
195	Hurricane Creek near Ico	7363276	2	90.4	0	.8	0
196	Derriusseaux Creek near Grapevine	7363435	2	77.0	0	0	0
197	Derriusseaux Creek near Rison	7363440	2	140	0	0	0
198	Big Creek near Pine Bluff	7363460	2	14.8	0	0	0
199	Big Creek near Pansy	7363465	2	153	0	0	0
200	Hudgin Creek near Pansy	7363700	2	109	0	0	0
201	Brown Creek near Lacey	7364010	2	14.6	0	0	0
202	L' Aigle Creek at Hermitage	7364020	2	172	0	0	0
203	Bayou Lapile at Strong	7364060	2	93.3	0	.4	<.1
204	Deep Bayou near Star City	7364130	2	99.2	0	0	0
205	Bayou Bartholomew at Garrett Bridge	7364133	2	380	0	5.7	1.0
206	Cutoff Creek near Selma	7364170	2	91.5	0	0	0
207	Chemin-A-Haut Creek near Berlin	7364250	2	116	0	.2	<.1
208	Bayou De Loure near El Dorado	7364600	2	78.2	0	2.7	.8
209	Little Comie Bayou near Junction City	7366100	2	106	0	1.1	0

Generalized Least Squares Regression to Estimate Low-Flow Statistics

Low flow at a site may be characterized by an index of low flow such as the 7-day, 2-year or 7-day, 10-year low flow, which is the discharge having a 2-year or 10-year recurrence interval derived from a frequency curve of lowest average flow for 7 consecutive days in a year. To estimate the flow characteristics (the 7-day, 2-year or 10-year low flows) at a site with no flow records, a regional regression relation is developed to relate the flow characteristics to basin characteristics. After transformation of variables to logarithms, the regional regression model may be written as

$$Y = X\beta + e,$$

where Y is a $n \times 1$ vector of transformed flow characteristics at n sites, X is an $n \times p$ matrix of $(p-1)$ basin characteristics augmented by a column of 1's, β is a $p \times 1$ vector of regression parameters to be estimated, and e is a $n \times 1$ vector of errors. The data used to estimate the regression coefficients, β , are flow data collected at stream gages in the region and at partial-record sites where a number of base-flow measurements have been made and correlated with daily-mean discharge at a continuous-record site (Stedinger and Thomas, 1985; Ludwig, 1992). The data for this analysis are shown in table 1. Only the sites with nonzero flow characteristics were used because the regression models apply only to sites with nonzero flow characteristics. The logistic regression described earlier in this report is used to predict whether or not the site has a nonzero flow characteristic.

The accuracy of an estimated flow characteristic based on recorded or measured flows may vary greatly from site to site depending upon, among other things, the length of record at a gaged site or number of base-flow measurements at a partial-record site. Other factors that affect accuracy include natural variability of flow and degree of autocorrelation in annual minimum flows. Ordinary least squares regression is not appropriate when the response variable, in this case the low-flow characteristic, is not observed with equal accuracy at all sites used in the regression.

Stedinger and Tasker (1985, 1986) documented the value of an estimated generalized least squares (EGLS) regression procedure for regional regression of streamflow characteristics. The EGLS estimator of β is

$$\beta = (X^T \Lambda^{-1} X)^{-1} X^T \Lambda^{-1} Y,$$

where it is assumed that the errors have zero mean $E[e]=0$, and covariance $E[ee^T]=\Lambda$.

The operational difficulty with this equation is that Λ is unknown and must be estimated from the data at hand. Stedinger and Tasker (1985) proposed that Λ be estimated as

$$\Lambda = \gamma^2 I + V,$$

where γ^2 is an estimate of the model error variance due to an imperfect model, I is the identity matrix, and V is a $n \times n$ matrix of sampling covariances that depend on record length, natural variability of the flow characteristic, cross correlation of sample response variables, and which flow characteristic is being estimated. Thus, the EGLS procedure uses the Λ matrix to assign different weights to observed flow characteristics based on their record length, cross correlation with flow characteristics at other sites and the model error variance, γ^2 . Tasker and Stedinger (1989) provide further details on how the elements of Λ are determined. The regression models are given in the sections on estimating the 7-day 2-year and 7-day 10-year low-flow values.

PHYSICAL PROPERTIES THAT SIGNIFICANTLY AFFECT LOW-FLOW CHARACTERISTICS

The low-flow characteristics of streams are directly related to the physical properties of the drainage basin. Drainage area (DA) is considered to be the predominant factor in explaining streamflow variability. Also, as suggested by Hines (1975), variations in low-flow yields can be closely associated with physiography. For example, drainage basins that are underlain by substrata that have high permeability and porosity almost always have greater base flows than do basins of equal size that are underlain by substrata with low permeability and porosity. Thus, when evaluating the variability of low flow, the type of bedrock underlying the drainage basin is also an important factor. Other factors such as soil type, forest cover, channel length, and slope that could potentially impact low-flow variability were found to be insignificant by comparison and were eliminated from the regionalization analyses. Therefore, drainage area and type of bedrock, herein represented by the term basin factor, are the only characteristics used in the regionalization of low-flow characteristics. The basin factor (BF) is defined as the percentage of drainage basin underlain by bedrock with high permeability.

Drainage areas are available for all active and inactive continuous-record gaging stations and partial-record gaging stations. These data are included in a series of drainage-area reports (Sullivan and Terry, 1970; Sullivan, 1974; Hines and Yanchosek, 1978; and Yanchosek and Hines, 1979). Drainage areas for continuous-record gaging stations also are available upon request from the basin and streamflow characteristics file of the National Water Data Storage and Retrieval System (WATSTORE), a computerized data base maintained by the U.S. Geological Survey. Drainage areas for the gaging stations used in this study are given in table 1.

The division of the study area into regions based upon the observed association between physiography and low-flow yields is discussed in the following section. Table 1 gives the number of the region in which each station is located and the basin factor value associated with that station.

LOW-FLOW DIVISIONS OF THE STATE

An examination of the variability in low-flow characteristics determined for gaging stations in the study area indicates a close correlation to the water-yielding characteristics of the geologic formations that underlie a given drainage basin. The association between physiographic area and low-flow yields in the State was first suggested by Hines (1975). Similar patterns of sustained base flow also were noted by Hunrichs (1983) in a report showing perennial streams in the State. More recently, the relation between bedrock type and base flow was pointed out in a report by Ludwig (1992). For regionalization purposes therefore, these interpretations were used as the initial basis for subdividing the State into regions of well-sustained and poorly-sustained base flow (plate 1). This subdivision was further supported by the variation in the predictive equations that resulted from the application of the regression models in each region.

Areas of Well-Sustained Base Flow

Region 1 encompasses most of the upper White River drainage basin and parts of the Arkansas River basin in Arkansas. The region is defined physiographically by the Springfield and Salem Plateaus and includes all geologic units stratigraphically below the Boone Formation. The region is underlain by a series of limestone and dolomite units and, because of this, exhibits numerous collapse features that are characteristic of karst terrain. Streams in the region are sustained by discharges from numerous springs, which issue from an apparently well-developed system of solution channels. The well-sustained nature of the spring flow is indicative of a regional source of water that is supplemented during extended periods of precipitation by a local component of flow.

Region 3 lies in the southern Ouachita Mountains and extends southward into the unconsolidated Coastal Plain deposits. It includes much of the upper Ouachita River basin and parts of the Red River basin. Base flows within the Ouachita Mountain section primarily are derived from the Arkansas Novaculite and Bigfork Chert Formations, which are composed primarily of fine-grained sandstone and chert. The formations have been extensively folded and faulted resulting in a high secondary porosity and permeability which has enhanced the recharge potential of the rocks.

Within the Coastal Plain segment of Region 3, base flow is derived as rejected recharge from the more productive aquifers in the area including the Sparta Sand and the Nacatoch Sand. A substantial contribution to base flow in the Coastal Plain is also from alluvial terrace deposits that cap the upland, interstream areas. These deposits are remnants of older alluvial systems that once blanketed the area but have since been eroded by the present-day stream systems. The base-flow contribution of the terrace deposits varies from place to place depending on the permeability of the sediments that make up the terraces. The occurrence of terraces is not limited to the highly permeable areas shown in plate 1, but, based on the evaluation of streamflow records, terraces generally are not as productive elsewhere as indicated by the poorly-sustained area in Region 2 in southern Arkansas.

Areas of Poorly-Sustained Base Flow

Region 2 includes two separate areas that are geologically and physiographically different but are similar with respect to base flow. The northern part of region 2 includes the Boston Mountains, Arkansas Valley, and the northern part of the Ouachita Mountains physiographic provinces (fig. 1). The area is underlain by consolidated rocks consisting primarily of sandstone and shale. The primary porosity and permeability of these deposits have been destroyed by compaction and deep burial. Only limited amounts of ground water are available from secondary openings such as joints and fractures in the rocks. However, the fractures are not extensive enough to supply the base flows of streams. Most streams in this area recede to zero flow each year.

The southern part of region 2 lies in the West Gulf Coastal Plain physiographic province. The area is underlain by unconsolidated deposits composed of sand, silt, and clay. The streams in the area, which encompasses much of south-central Arkansas, generally do not have sustained base flow because in part the stream channels are not incised deeply enough to intercept the water table and, in part, because the surficial deposits have low permeability and porosity.

PREDICTIVE EQUATIONS FOR ESTIMATING LOW-FLOW CHARACTERISTICS

The regression models described earlier in this report were applied in each of the three regions in the study area. The models were calibrated using the known data for stream gaging stations given in table 1. Predictive equations resulting from the calibrated models can be used to estimate selected low-flow characteristics at ungaged sites in each region.

Low-flow characteristics $Q_{7,2}$ and $Q_{7,10}$ can be estimated at ungaged sites by the following three-step method. The first step is to estimate the probability that the 7-day annual minimum flow is zero (PRZERO) at the ungaged site of interest by the method explained in the following section. The second step uses the estimated probability of zero flow, PRZERO, to determine if the estimated value of $Q_{7,2}$ or $Q_{7,10}$ is zero or needs to be estimated from one of the regional equations.

Estimating Probability of Zero Flow at an Ungaged Site

To estimate the probability (PRZERO) of the 7-day annual minimum flow being zero for an arbitrary year at an ungaged site, determine (1) the drainage area in square miles, DA, above the site, (2) the region (1, 2, or 3) in which the site is located, and (3) the percentage of the basin drainage area, BF, that is in the sustained base flow areas indicated on the map in plate 1. PRZERO is computed as follows:

$$PRZERO = 1 - \{exp(P) / [1+exp(P)]\},$$

where, if the site in question is in region 1 or 3,

$$P = 1.34 + 0.00163(DA) + 0.0228(BF),$$

or, if the site in question is in region 2,

$$P = -0.144 + 0.0041(DA).$$

Estimating Seven-Day Two-Year Low-Flow Values

If the value for PRZERO from the above equation is greater than 0.5, that is, there is a greater than 50 percent chance that the flow at the desired location is zero, then $Q_{7,2}$ is estimated to be zero. However, if PRZERO is estimated to be less than or equal to 0.5, then $Q_{7,2}$ can be estimated from one of the regional equations below. For a site in region 1, the equation is:

$$Q_{7,2} = 0.021(DA)^{0.554}(BF+1)^{0.713} \quad (1)$$

For a site in region 2, the equation is:

$$Q_{7,2} = 0.0025(DA)^{0.977} \quad (2)$$

For a site in region 3, the equation is:

$$Q_{7,2} = 0.0053(DA)^{0.740}(BF+1)^{0.795} \quad (3)$$

Estimating Seven-Day Ten-Year Low-Flow Values

If PRZERO is estimated to be greater than 0.1, that is there is a greater than 90 percent chance that the flow is zero, then $Q_{7,10}$ is estimated to be zero. However, if PRZERO is estimated to be less than or equal to 0.1, then $Q_{7,10}$ can be estimated from one of the regional equations below. For a site in region 1, the equation is:

$$Q_{7,10} = 0.0031(DA)^{0.58}(BF+1)^{0.915} \quad (4)$$

For a site in region 2, the equation is:

$$Q_{7,10} = 0.0010(DA)^{0.986} \quad (5)$$

For a site in region 3, the equation is:

$$Q_{7,10} = 0.00049(DA)^{0.768}(BF+1)^{1.104} \quad (6)$$

UNCERTAINTY AND LIMITATIONS OF PREDICTIVE EQUATIONS

Prediction Interval Estimates

The regional regression analysis not only provides predictive equations for estimating $Q_{7,2}$ and $Q_{7,10}$, but can also provide an estimate of the uncertainty associated with the estimate. One measure of uncertainty is the prediction interval of an estimate at an ungauged site. A $100(1-\alpha)$ prediction interval for the true low-flow characteristic, $\theta_{7,\tau}$, at an ungauged site can be computed by

$$(1/T)Q_{7,\tau} < \theta_{7,\tau} < (T)Q_{7,\tau}$$

where the value of T can be computed for each of the six regional estimating equations in the previous section by the following method.

Let x_i represent a row vector of logarithms of basin characteristics at ungauged site i augmented by 1. For example, for a site with $DA=50 \text{ mi}^2$ and $BF=15$ percent,

$$x_i = [1, \log_{10}(50), \log_{10}(15+1)].$$

Then the standard error of prediction at site i, in log units, would be given by:

$$S_i = [\gamma^2 + x_i U x_i']^{0.5},$$

where γ^2 and U are the model error variance and the covariance matrix for the regression coefficients, respectively, associated with the estimating equation, and

x_i' is the transpose of x_i . The value for T is then calculated by

$$\log_{10}(T) = t_{(\alpha/2, n-p)} S_i,$$

where $t_{(\alpha/2, n-p)}$ is the critical value of the t-distribution for n-p degrees of freedom and is tabulated in many statistical texts, n is the number of observations used in the regression analysis, and

p is the number of basin characteristics (explanatory variables) used in the regression plus one.

The values for γ^2 , U, n, and p are given in table 2 for each of the six regional predictive equations.

Limitations of Predictive Equations

The observed data used to calibrate the regression models were collected at sites with drainage basin areas ranging from 3.2 to 829 mi^2 in region 1, 3.3 to 764 mi^2 in region 2, and 0.19 to 896 mi^2 in region 3. The resulting predictions could have errors much larger than those estimated from the observed data for basins whose size falls outside these ranges. If the uncertainty in the predictions, as measured by the prediction interval, is too great for an intended use, an improved estimate at a site can be made by making several low-flow discharge measurements at the site on different base flow recessions and correlating these flow data with concurrent flow data at a nearby gaging station.

Table 2.--Values needed to calculate confidence intervals

[n is the number of sites used in the regression, p is the number of regression coefficients estimated (including the regression constant), t is the critical value to the t-distribution used to calculate 90 percent prediction intervals, γ is the model standard error, in log units, and U is the $(p \times p)$ covariance matrix of the regression coefficients]

Equation number	Dependent variable	n	p	t	γ	U		
Region 1								
1	Q _{7,2}	57	3	1.68	0.502	0.16798	-0.05657	-0.02418
						-0.05657	.02808	-.00095
						-0.02418	-.00095	.01480
4	Q _{7,10}	53	3	1.68	.615	.32825	-.09237	-.06919
						-.09237	.04426	.00044
						-.06919	.00044	.03788
Region 2								
2	Q _{7,2}	71	2	1.67	.487	.15957	-.06666	
						-.06666	.02991	
5	Q _{7,10}	12	2	1.81	.290	1.5718	-.5784	
						-.5784	.2166	
Region 3								
3	Q _{7,2}	86	3	1.66	.476	.15280	-.02815	-.04715
						-.02815	.01108	.00315
6	Q _{7,10}	75	3	1.67	.639	-.04715	.00315	.02108
						.32321	-.05416	-.10868
						-.05416	.02106	.00656
						-.10868	.00656	.05071

Fit of Data to the Generalized Least Squares Regression Model

One measure of the fit of observed data to the model is the proportion of total variance in the observed flow value that is explained by the model, R^2 . This value is calculated as:

$$R^2 = (\text{Variance of } y - \gamma^2) / (\text{Variance of } y)$$

in which y is the log transformed low flow and γ is the estimated model standard error given in table 2. The values of R^2 for each of the predictive equations are as follows:

For Region 1: Equation 1, $R^2 = 0.50$

Equation 4, $R^2 = 0.41$

For Region 2: Equation 2, $R^2 = 0.44$

Equation 5, $R^2 = 0.75$

For Region 3: Equation 3, $R^2 = 0.61$

Equation 5, $R^2 = 0.47$

EXAMPLE COMPUTATIONS

Suppose estimates of $Q_{7,2}$ and $Q_{7,10}$ are needed for an ungaged site in region 1 with $DA=50 \text{ mi}^2$ and $BF=15$ percent. The first step is to calculate PRZERO. In this case:

$$P = 1.34 + 0.00163(50) + 0.0228(15) = 1.7635$$

and

$$PRZERO = 1 - \{ \exp(1.764) / [1 + \exp(1.764)] \} = 0.15$$

Since PRZERO is less than 0.5, $Q_{7,2}$ is estimated by equation 1,

$$Q_{7,2} = 0.021(50)^{0.554}(15+1)^{0.713} = 1.32 \text{ ft}^3/\text{s}.$$

Ninety percent prediction interval estimates can be made as follows:

From table 2, $\gamma^2 = 0.502^2 = 0.252$, and $t = 1.68$.

The vector of basin characteristics is $x_i = [1, \log_{10}(50), \log_{10}(15+1)]$, and the 3×3 matrix U is:

$$U = \begin{matrix} & 0.16798 & -0.05657 & -0.02418 \\ \begin{matrix} \mathbf{U} = \end{matrix} & -0.05657 & 0.02808 & -0.00095 \\ & -0.02418 & -0.00095 & 0.01480 \end{matrix}$$

$$S_i = [\gamma^2 + x_i U x_i]^{0.5} = [0.252 + 0.0162]^{0.5} = 0.518, \text{ and } T = 10^{0.518(1.68)} = 7.42.$$

Therefore, an approximate 90 percent prediction interval is $1.32/7.42 < Q_{7,2} < 1.32(7.42)$ or $(0.2, 9.8)$. This indicates that there is a 90 percent chance that the unknown discharge ($Q_{7,2}$ in this case) is within the range of 0.2 and 9.8 ft^3/s . Since PRZERO is greater than 0.1, $Q_{7,10}$ is estimated to be zero.

EXTRAPOLATION OF LOW-FLOW DATA

Regional flow equations presented herein can be used to estimate low-flow characteristics at any desired site on streams in the study area. However, it is commonly desirable to estimate the characteristics at an ungaged site that is on a stream where low-flow characteristics are known at a nearby continuous-record or partial-record gaging station. Within limits, the low-flow characteristics can be transferred from a gaged site either upstream or downstream, to an ungaged site using a proration by drainage areas. The relation is defined as follows:

$$7Q_{T,u} = 7Q_{g} \left(\frac{A_u}{A_g} \right)$$

where, $Q_{7,T}$ is average minimum 7-consecutive day discharge for a T-year recurrence interval (cubic feet per second),

u is ungaged site where low-flow values are to be determined,

g is gaged site where low-flow values are know, and

A is drainage area (square miles).

Limitations pertaining to the use of the relation include the following: (1) the drainage area of the ungaged site must be less than 50 percent greater or smaller than the drainage area of the gaged site, and (2) the extrapolation of the low-flow characteristics should not be extended beyond the confluence of a major tributary stream. A major tributary stream is defined herein as any stream that causes the drainage area of the gaged stream to change more than 25 percent at the confluence.

PERSONAL COMPUTER SOFTWARE FOR COMPUTING LOW-FLOW CHARACTERISTICS

A FORTRAN computer program has been written to perform the rather tedious computations. A disk containing the program is included at the end of this report (in pocket). The program is compatible with the MS DOS¹ operating system which is available on many personal computers. The program is activated by typing "ARK" after inserting the disk into the proper disk drive. The user is asked to input the region (1, 2, or 3) from plate 1, the drainage area (DA), and the basin factor (BF) of the site of interest. The program is driven by queries and prompts and requires no other user documentation. The source code for the program is given in Appendix 1.

SUMMARY

Regression analysis was selected as the methodology for regionalizing low-flow characteristics in the study area. Suggestions made by earlier investigators, later supported by the performance of the regression models, led to the division of the study area into three regions based upon physiography. Data collected at stream-gaging stations in two of the regions reflect well sustained base flows. Conversely, data collected at stream-gaging stations in the third reflect poorly sustained base flow. Much of the area in the former two regions is underlain by substrata that readily yield water to streams. Substrata underlying the latter region yields relatively little water to streams. In drainage basins underlain by substrata that readily yield water, Basin Factor, was a significant independent variable in the regression models. Drainage area was a significant independent variable in the regression models for all three regions.

A logistic regression model and a generalized least squares regression model were calibrated for each region. The calibration of the logistic regression model yielded predictive equations that can be used to estimate the probability that the 7-day annual mean flow at an ungaged site is zero. Calibration of the generalized least squares model in each region resulted in predictive equations that can be used to estimate the 7-day 2-year and the 7-day 10-year low flows at ungaged sites. In each region, if the probability of zero flow is greater than 0.5, then the $Q_{7,2}$ is estimated to be zero. If it is less than or equal to 0.5, then the estimated $Q_{7,2}$ should be computed by the appropriate predictive equation for that region. Further, if the probability of zero flow is greater than 0.1 at an ungaged site, then the $Q_{7,10}$ should be estimated to be zero. However, if it is less than or equal to 0.1 then the estimated $Q_{7,10}$ should be computed by the appropriate predictive equation for that region.

An interactive FORTRAN computer program was written to solve the predictive equations using values for the independent variables input by the user. This program is provided on a personal computer diskette and in printed form as a part of this report.

¹Use of brand name in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

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```

character*32 site
  character*80 hdng,temp,tl1,tl2,tl3,tl4,tl5,tl6
  character*2  regnum
  character*3  go
  real*4 lda, lpc, da, pc
  integer*4 region, warn
  common /c1/ lda, lpc, da, pc, q72, q710,
+   b72, b710, u72, u710, warn
c
c
  tl1(19:) = 'Flow Duration and Low-Flow Characteristics'
  tl2(26:) = 'of Selected Arkansas Streams'
  tl3(39:) = 'By'
  tl4(27:) = 'A.H. Ludwig and Gary Tasker'
  tl5(13:) =
+ 'This program computes estimates of 7-day 2-year and'
  tl6(13:) =
+ '7-day 10-year flow values at ungaged sites in Arkansas.'
6000 continue
  write(*,*) char(27), '[2J'
  write(*,*) char(27), '[2;1H'
  write(*,*) char(27), '[1m'
  write(*,'(A/)' ) tl1
  write(*,'(A/)' ) tl2
  write(*,'(A/)' ) tl3
  write(*,'(A/)' ) tl4
  write(*,*) char(27), '[0m'
  write(*,*) char(27), '[1;33m'
  write(*,'(A)' ) tl5
  write(*,'(A//)' ) tl6
  write(*,*) char(27), '[0m'
  write(*,2000)
c 2000 format('  Enter site id, if any (<cr> to end)')
2000 format('  Enter site id, if any (q or Q to quit)')
  read(*,1010)site
  if (site .EQ. 'q' .OR. site .EQ. 'Q') then
    goto 200
  else if (site .EQ. ' ') then
    site = '<no site id given>'
  endif
1010 format(a32)
400 continue
  write(*,2010)
2010 format(
+'  Enter region number from figure #2 (1, 2, 3, or 99 to quit)')
  read(*,*)region
  if (region .EQ. 99 ) then
    goto 200
  else if((region .LT. 1) .OR.
+ (region .GT. 3 .AND. region .LT. 99) .OR.
+ (region .GT. 99)) then
    write(*,*) char(27), '[0m'
    write(*,*) char(27), '[1;33m'
    write(*,'(A/)' ) ' Invalid region: Please re-enter value.'

```



```

        write(*,*) char(27), '[0m'
        goto 400
    endif
    write(*,2020)
2020 format(' Enter drainage area, in square miles')
    read(*,*)da
    lda=alog10(da)
    if(region.eq.1.or.region.eq.3) then
410     continue
        write(*,2030)
2030     format(' Enter percent of basin in high yield area (0-100)')
        read(*,*)pc
        if (pc .LT. 0 .OR. pc .GT. 100) then
            write(*,*) char(27), '[1;33m'
            write(*,*)
+           ' Percent value out of range: Please re-enter value.'
            write(*,*) char(27), '[0m'
            goto 410
        end if
        lpc=alog10(pc+1.0)
    end if

c
c
    write(*,*) char(27), '[2J'
    if(region.eq.1)call r1
    if(region.eq.2)call r2
    if(region.eq.3)call r3

c
c
c     write(*,2999)site, region
c 2999 format(' Estimate of low flows for ',a,' in region',i2,/,
c     +' Flow Char.',t20,'Estimated',t35,
c     +'90 percent prediction interval',/,t20,'Value',t35,
c     +'Lower limit      Upper limit',/)

    write(*,*) char(27), '[2;1H'
    write(*,*) char(27), '[1m'
    write(*,'(A/)' ) t11
    write(*,'(A/)' ) t12
    write(*,'(A/)' ) t13
    write(*,'(A/)' ) t14
    write(*,*) char(27), '[0m'
    write(*,*) char(27), '[1;33m'

    temp(1:27) = ' Estimate of low flows for '
    temp(28:) = site
    i = 1
    if (site .EQ. '<no site id given>') then
        i = 19
    else
500     continue
        if (site(i:i) .NE. ' ') then
            i = i + 1
            goto 500
        end if
    end if

```

```

        endif
    endif
    write(regnum,'(I2)') region
    temp(28+i:) = 'in region '
    temp(38+i:) = regnum
    hdng = ' '
    hdng((80-(39+i))/2:) = temp
    write(*,'(A//)') hdng
    write(*,*) char(27), '[0m'
2999 format(' Flow Char.',t20,'Estimated',t35,
+'90 Percent Prediction Interval',/,t20,'Value',t35,
+'Lower limit   Upper limit',/)
    write(*,2999)
    write(*,3000) q72,b72, u72
    write(*,3001) q710,b710, u710
3000 format(1x,'Q(7,2)',t9, 3f15.1)
3001 format(1x,'Q(7,10)',t9, 3f15.1)
    if(warn.eq.1)write(*,3002)
3002 format(//,' WARNING Estimate beyond range of observed data')
C
c      stop
    go = ' '
6001 write(*,3003)
3003 format(///,' Do you have another site?(<cr> = quit)')
    read(*,3004) go
3004 format(a3)
    if (go .eq. 'y' .or. go .eq. 'Y' .or. go .eq. 'yes'
>     .or. go .eq. 'YES') then
        goto 6000
    elseif (go .eq. ' ' .or. go .eq. 'q' .or.
>         go .eq. 'Q') then
        goto 200
    else
        write(*,3005)
3005     format (//,' Improper response.')
        goto 6001
    endif
200 end
    subroutine rl
    real*4 lda, lpc, da, pc
    integer*4 region, warn
    common /c1/ lda, lpc, da, pc, q72, q710,
+   b72, b710, u72, u710, warn
    real*4 x(1,3),u2(3,3),xt(3,1),temp1(1,3),xtx(1,1),u10(3,3)
    data u2 /0.16798, -0.056570, -0.024181,
+         -0.056570, 0.028083, -0.0009464,
+         -0.024181, -0.0009464, 0.014799 /
    data u10 / 0.32825, -0.092365, -0.069192,
+            -0.092365, 0.044257, 0.00043817,
+            -0.069192, 0.00043817, 0.037883 /
C
c compute przero
C
    p=1.34267+0.0016278*da+0.02275113*pc

```

```

prz=1-(exp(p)/(1+exp(p)))
q72=0.0209247*da**0.5540*(pc+1)**0.7127
q710=0.003141*da**.5892*(pc+1)**.9145

```

c

c compute predicion limits

c

```

x(1,1)=1.0
x(1,2)=lda
x(1,3)=lpc
xt(1,1)=1.0
xt(2,1)=lda
xt(3,1)=lpc
call multiply(temp1,x,u2,1,3,3,1,1,3)
call multiply(xtx,temp1,xt,1,3,1,1,1,3)
v=xtx(1,1)
s=sqrt(.502**2+v)
t=10**(1.68*s)
u72=q72*t
b72=q72/t
if (prz.gt.0.5) then
    q72=0.0
    b72=0.0
end if
warn=0
if (da.gt.540.) warn=1
if (da.lt.3.) warn=1
call multiply(temp1,x,u10,1,3,3,1,1,3)
call multiply(xtx,temp1,xt,1,3,1,1,1,3)
v=xtx(1,1)
s=sqrt(.615**2+v)
t=10**(1.68*s)
u710=q710*t
b710=q710/t
if (prz.gt.0.1) then
    q710=0.0
    b710=0.0
end if
return
end
subroutine r2
real*4 lda, lpc, da, pc
integer*4 region, warn
common /c1/ lda, lpc, da, pc, q72, q710,
+ b72, b710, u72, u710, warn
real*4 x(1,2), u2(2,2), xt(2,1), temp1(1,2), xtx(1,1), u10(2,2)
data u2 /0.15957, -0.066655, -0.066655, 0.029905 /
data u10 /1.5718, -0.57840, -0.57840, 0.21663 /

```

c

c compute przero

c

```

p=-0.144119+0.0041436*da
prz=1-(exp(p)/(1+exp(p)))
q72=0.002527*da**0.9765
q710=0.001047*da**.9863

```

```

c
c compute predicion limits
c
  x(1,1)=1.0
  x(1,2)=lda
  xt(1,1)=1.0
  xt(2,1)=lda
  call multiply(temp1,x,u2,1,2,2,1,1,2)
  call multiply(xtx,temp1,xt,1,2,1,1,1,2)
  v=xtx(1,1)
  s=sqrt(.487**2+v)
  t=10**(1.67*s)
  u72=q72*t
  b72=q72/t
  if (prz.gt.0.5) then
    q72=0.0
    b72=0.0
  end if
  warn=0
  if(da.gt.570.)warn=1
  if(da.lt..2)warn=1
  call multiply(temp1,x,u10,1,2,2,1,1,2)
  call multiply(xtx,temp1,xt,1,2,1,1,1,2)
  v=xtx(1,1)
  s=sqrt(.290**2+v)
  t=10**(1.81*s)
  u710=q710*t
  b710=q710/t
  if (prz.gt.0.1) then
    q710=0.0
    b710=0.0
  end if
  return
end
subroutine r3
  real*4 lda, lpc, da, pc
  integer*4 region, warn
  common /c1/ lda, lpc, da, pc, q72, q710,
+   b72, b710, u72, u710, warn
  real*4 x(1,3),u2(3,3),xt(3,1),temp1(1,3),xtx(1,1),u10(3,3)
  data u2 / 0.15280, -0.028150, -0.047149,
+   -0.028150, 0.011081, 0.0031482,
+   -0.047149, 0.0031482, 0.021081 /
  data u10 /0.32321, -0.054161, -0.10868,
+   -0.054161, 0.021063, 0.0065608,
+   -0.10868, 0.0065608, 0.050705 /
c
c compute przero
c
  p=1.34267+0.0016278*da+0.02275113*pc
  prz=1-(exp(p)/(1+exp(p)))
  q72=0.005324*da**0.7401*(pc+1)**0.7951
  q710=0.000489*da**.7682*(pc+1)**1.1041
c

```

```
c compute predicion limits
```

```
c
```

```
  x(1,1)=1.0
  x(1,2)=lda
  x(1,3)=lpc
  xt(1,1)=1.0
  xt(2,1)=lda
  xt(3,1)=lpc
  call multiply(temp1,x,u2,1,3,3,1,1,3)
  call multiply(xtx,temp1,xt,1,3,1,1,1,3)
  v=xtx(1,1)
  s=sqrt(.476**2+v)
  t=10**(1.66*s)
  u72=q72*t
  b72=q72/t
  if (prz.gt.0.5) then
    q72=0.0
    b72=0.0

  end if
  warn=0
  if (da.gt.760.) warn=1
  if (da.lt.3.) warn=1
  call multiply(temp1,x,u10,1,3,3,1,1,3)
  call multiply(xtx,temp1,xt,1,3,1,1,1,3)
  v=xtx(1,1)
  s=sqrt(.639**2+v)
  t=10**(1.67*s)
  u710=q710*t
  b710=q710/t
  if (prz.gt.0.1) then
    q710=0.0
    b710=0.0
  end if
  return
end
subroutine multiply(prod,x,y,k1,k2,k3,n1,n2,n3)
```

```
c
```

```
c matrix multiplication
```

```
c
```

```
  dimension prod(n1,k3), x(n2,k2), y(n3,k3)
  do 1 i=1,k1
  do 3 k=1,k3
  sum=0.0
  do 2 j=1,k2
2 sum=sum+x(i,j)*y(j,k)
3 prod(i,k)=sum
1 continue
  return
end
```

