A REGIONAL RESERVOIR STORAGE ANALYSIS FOR EASTERN MASSACHUSETTS AND RHODE ISLAND

By
Gary D. Tasker[1]

Abstract

Regionalized relationships between reservoir storage and uniform reservoir outflow resulting from redistribution of natural flow by storage are presented for streams in eastern Massachusetts and Rhode Island. The relationships are given in terms of percent chance that the reservoir would become empty and are based on long-term streamflow records. They take into account seasonal and year to year variations in streamflow by use of hydrologic indices which can be estimated for ungaged sites. The indices are the 7-day, 2-year low flow and the coefficient of variation of annual discharge.

Introduction

Many reservoirs are built on streams so that demands for water during periods of insufficient streamflow can be met by stored water. Implied in reservoir design is some chance that the reservoir will be too large and waste money or too small and fail to meet demands. The anticipated probabilities that the reservoir will be inadequate to meet expected demands is of primary concern in determining benefits of a water development.

Storage requirements traditionally have been calculated by a mass-curve analysis of streamflow records (Rippl, 1883) in which the required storage equals the difference between the cumulated desired flow and the cumulated actual flow during a critical period. This methods appears less than satisfactory for estimating probabilities of failure to meet demands because of its dependence on the sequence of recorded flows.

The storage analysis presented herein generally follows procedures recommended by Riggs and Hardison (1973) in which storage requirements are calculated by a combination of probability routing (Langbein, 1958) and the mass-curve method. It is not dependent on the exact sequence of streamflow events and leads to more reliable estimates of probabilities.

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[1]Hydrologist, U.S. Geological Survey, Boston, Mass.

Development of Regional Draft-Storage Relations

The method of regionalizing draft-storage relations described here can furnish useful hydrologic information for comparative storage studies and preliminary reservoir design. The examples of regionalized draft-storage relationships take into account the seasonal and year to year variations in streamflow and are based on data collected at 12 stream-gaging stations in Massachusetts and Rhode Island (Figure 5 and Table 1). Final design of major reservoir projects requires use of more sophisticated procedures such as synthesizing a long flow record. Also, when estimating storage requirements to provide a yield for a specific location, adjustments should be made for the effects of reservoir evaporation and seepage, for the reduction in reservoir capacity because of sedimentation, and for the possible modification in capacity for flood control and recreation.

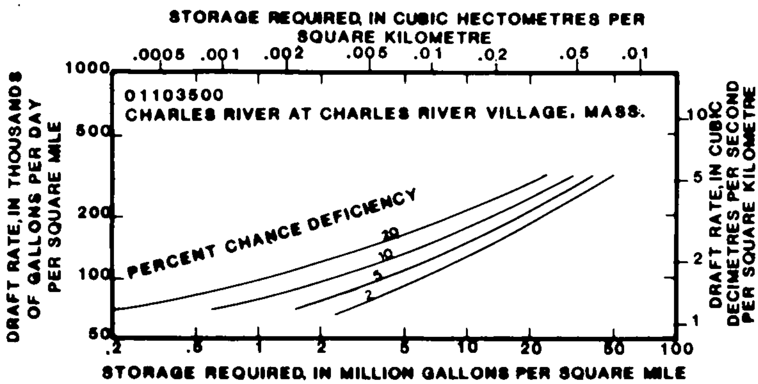

Figure 1: Draft-storage-deficiency curve for Charles River at Charles River Village, Massachusetts.

Determination of Seasonal Storage Requirements

Some demands for water greater than minimum streamflow can be met throughout a year by impounding water during the high-flow periods for release during subsequent low-flow periods. This impoundment is termed seasonal storage. The relationship between seasonal storage, draft rate,[1] and percent chance of deficiency was determined at each of the 12 gaging stations by the following steps:

A) From daily streamflow records, the storage required for a given draft rate for each year of record was determined by the mass-curve method (Rippl, 1883).

[1]For definitions of terms used in this report, see listing at end of text.

B) From the annual storages in step A, a frequency curve was prepared relating the magnitude of annual storage for each of various draft rates to frequency of occurrence.

C) Draft-storage curves for several chances of deficiency were then prepared from the frequency curves constructed in step B. The draft-storage curves for Charles River at Charles River Village, Massachusetts, are shown in Figure 1.

This type of analysis assumes the reservoir is full on April 1 of each year. Therefore, it is limited to draft rates low enough to allow the proposed reservoir to be refilled by April 1 of each year. The data for the 12 stations indicate only draft rates less than about 0.5 $ft^3s^{-1}mi^{-2}$ (5.5 $dm^3s^{-1}km^{-2}$) meet this requirement.

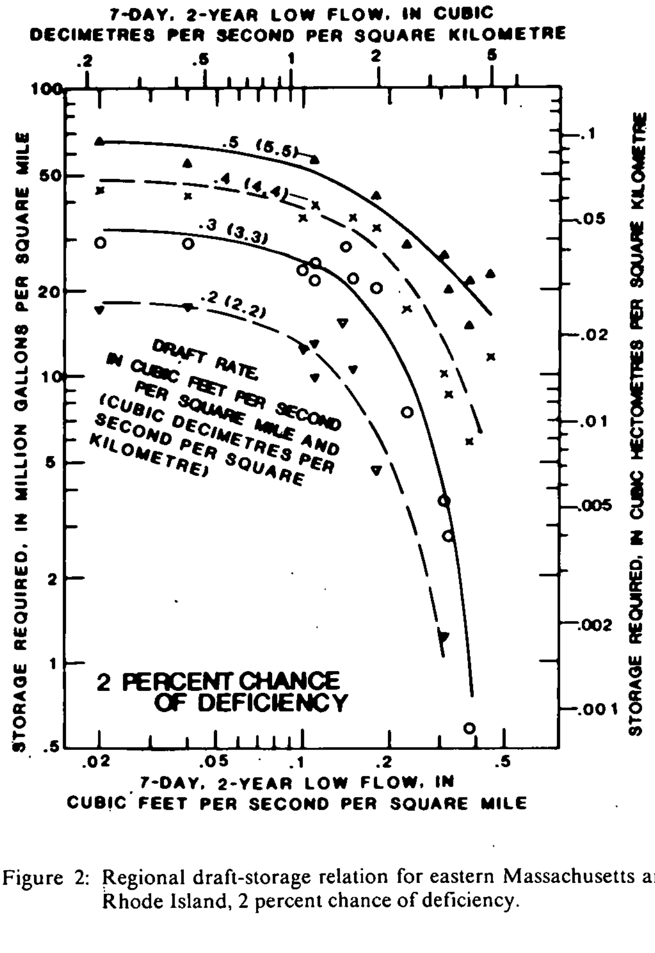

Figure 2: Regional draft-storage relation for eastern Massachusetts and Rhode Island, 2 percent chance of deficiency.

Regionalization of Seasonal Storage Requirements

Seasonal storage requirements differ from site to site in the study area largely because of differences in the size of drainage basins and differences in the seasonal variability of streamflow. The effect of differences in size of drainage basins is accounted for by analyzing the records on a per unit area basis. The effect of differences in seasonal variability of streamflow is accounted for by using an index of streamflow variability, namely the 7-day, 2-year low flow, in cubic feet per second per square mile or cubic decimetres per second per square kilometre. Figures 2, 3 and 4 show the relation between draft rate, storage requirements, and the 7-day, 2-year low flow for chances of deficiency of 2, 5, and 10 percent, respectively.

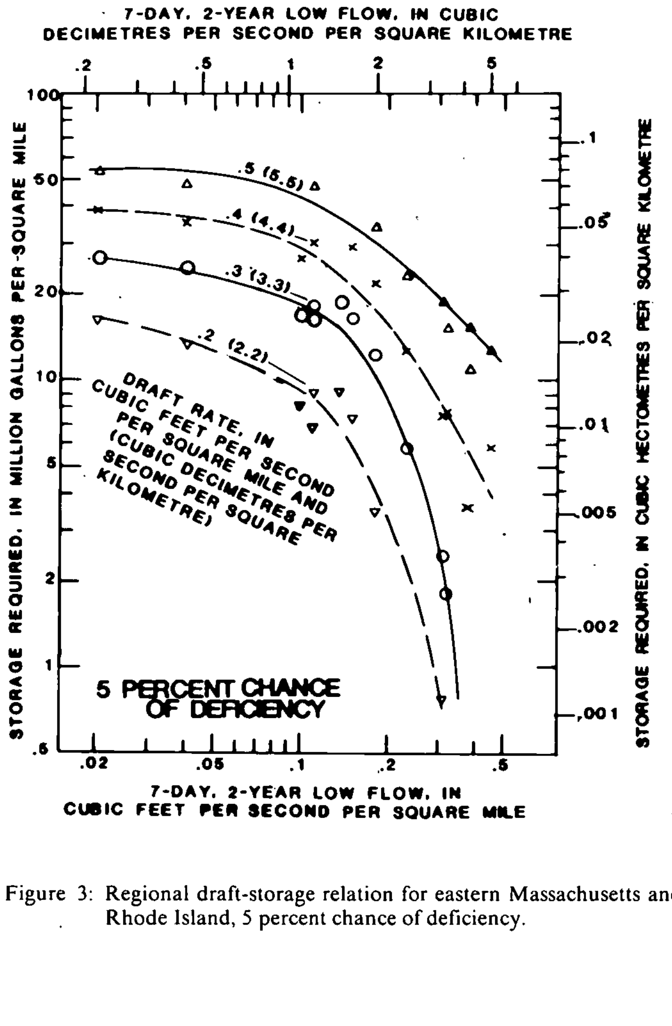

Figure 3: Regional draft-storage relation for eastern Massachusetts and Rhode Island, 5 percent chance of deficiency.

The 7-day, 2-year low flow was selected as an index of seasonal variability of streamflow because it can be easily estimated from a few base-flow measurements (Riggs, 1965) or from maps of ground-water availability (Tasker, 1972) at nonmeasured sites in southeastern Massachusetts. In addition, the U.S. Geological Survey has made estimates of the 7-day, 2-year low flow at more than 100 sites in the area (Brackley, Fleck, and Meyer, 1973; Walker, Wandle, and Caswell, 1974; Williams, Farrell, and Willey, 1973; Williams and Tasker, 1974a, 1974b; and unpublished data in files).

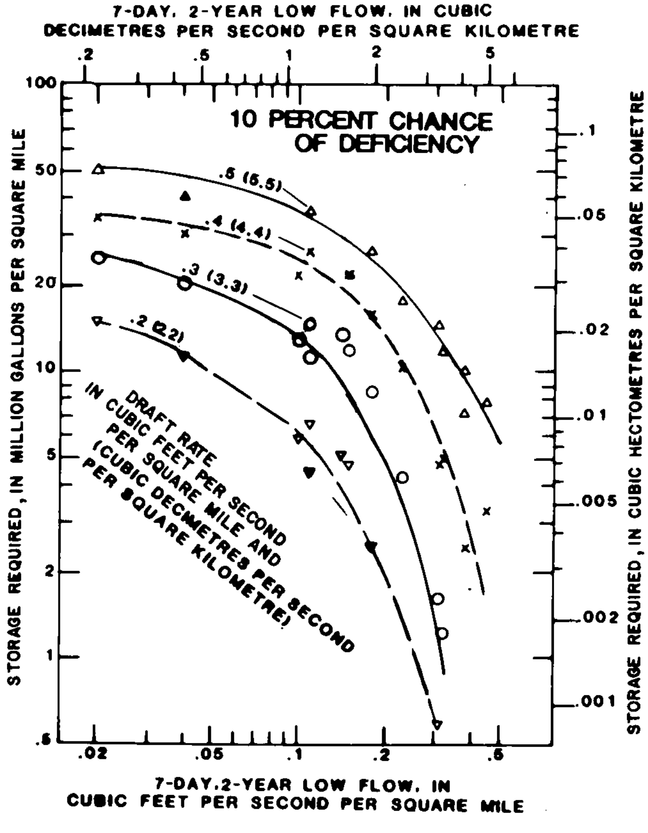

Figure 4: Regional draft-storage relation for eastern Massachusetts and Rhode Island, 10 percent chance of deficiency.

Determination of Regional Carryover Storage Requirements

In eastern Massachusetts and Rhode Island, to supply draft rates in excess of about 0.5 $ft^3s^{-1}mi^{-2}$ (5.5 $dm^3s^{-1}km^{-2}$) with a chance of deficiency of 20 percent or less requires water stored during wet years to be carried over for release during dry years. The volume required to store this extra water is termed carryover storage. Carryover storage can be estimated by probability routing as shown by Langbein (1958). Langbein (1961) and Hardison (1964, 1966) have generalized the method of probability routing if the annual discharges can be described by a normal, log-normal, or Weibull distribution.

Based on a study of 180 gaging stations throughout the United States, Hardison (1966) has provided criteria for determining whether annual discharge may be described by one of the three distributions. The criteria, based on the statistics of annual discharge, are as follows:

1) If the skew coefficient with annual discharge in log units (g) is greater than –0.2, a log-normal distribution is appropriate.
2) If the skew coefficient with annual discharge in cubic feet per second is less than +0.2 or if the coefficient of variation (C_v) is less than 0.25, a normal distribution is appropriate.
3) If neither the log-normal nor normal distribution is appropriate, a Weibull distribution can be used, provided the skew coefficient (g) is not less than –1.5.

Using these criteria, a normal distribution of annual discharge, characterized by MAR (mean annual runoff) and C_v (coefficient of variation) was judged appropriate for the gaging stations in the area. Therefore, it is possible to regionalize carryover storage requirements by estimating MAR and C_v on a regional basis. Knox and Nordensen (1955) have mapped variations in MAR, indicating a general increase from about 20 inches (508 mm) south of Providence. Data available since Knox and Nordensen's study indicate that the MAR for the area north of Boston should be revised to about 22 inches (560 mm). Regional variations in C_v, indicated by long-term records of gaging stations (Table 1), are shown in Figure 5.

Combining Seasonal and Carryover Storage Requirements

Carryover storage alone does not adequately describe total storage requirements because it does not account for seasonal variability of streamflow. However, total storage requirements (combined seasonal and carryover) may be estimated as suggested by Beard (1964) and modified by Riggs and Hardison (1973). Riggs and Hardison estimate total storage requirements by adding a seasonal storage adjustment to carryover storage. The adjustment is calculated as follows: (1) For the draft rate when carryover storage first becomes a factor, the adjustment is equal to the seasonal storage. (2) The adjustment then is increased linearly with draft rate to 0.4 of

TABLE 1
STATIONS USED IN ANALYSIS, STATISTICS OF ANNUAL DISCHARGE, AND 7-DAY, 2-YEAR LOW FLOWS.

STATION NUMBER	STATION NAME AND LOCATION	DRAINAGE AREA, IN MI²	PERIOD OF RECORD	STATISTICS OF ANNUAL MEAN DISCHARGE							7-DAY, 2-YEAR LOW FLOW, IN FT³/S
				UNITS OF ANNUAL DISCHARGE FT³/S				UNITS OF ANNUAL DISCHARGE LOGS OF FT³/S			
				MEAN	COEFFICIENT OF VARIATION	COEFFICIENT OF SKEW	SERIAL CORRELATION COEFFICIENT	STANDARD DEVIATION	COEFFICIENT OF SKEW	SERIAL CORRELATION COEFFICIENT	
01096000	Squannacook River near West Groton, Mass.	62.8	1950-72	106	0.324	-0.157	0.163	0.165	-1.09	0.277	9.10
01097000	Assabet River at Maynard, Mass.	116	1942-72	178	.305	- .131	.293	.150	- .855	.316	13.1
01101000	Parker River at Byfield, Mass.	21.6	1946-72	35.2	.291	- .281	.123	.151	-1.21	.238	.76
01103500	Charles River at Charles River Village, Mass.	184	1938-72	292	.284	- .104	.286	.138	- .866	.308	26.9
01106000	Adamsville Brook at Adamsville, R.I.	7.91	1941-72	14.1	.260	- .366	.119	.128	- .954	.185	.16
01108000	Taunton River at State Farm near Bridgewater, Mass.	260	1930-72	457	.267	- .481	.237	.136	-1.22	.260	46.4
01109000	Wading River near Norton, Mass	42.4	1926-72	70.6	.255	- .578	.096	.130	-1.19	.125	4.80
01111500	Branch River at Forestdale, R.I.	91.2	1941-72	162	.258	- .088	.191	.122	- .708	.220	20.6
01114500	Wonnasquatucket River at Centerdale, R.I.	38.3	1942-72	69.0	.254	- .345	.164	.124	- .972	.156	17.1
01117500	Pawcatuck River at Wood River Junction, R.I.	100	1942-72	189	.234	- .347	.145	.111	- .749	.167	37.8
01118000	Wood River at Hope Valley, R.I.	72.4	1942-72	147	.218	- .314	.169	.104	- .912	.198	27.5
01118500	Pawcatuck River at Westerly, R.I.	295	1942-72	557	.230	- .191	.190	.107	- .651	.213	95.2

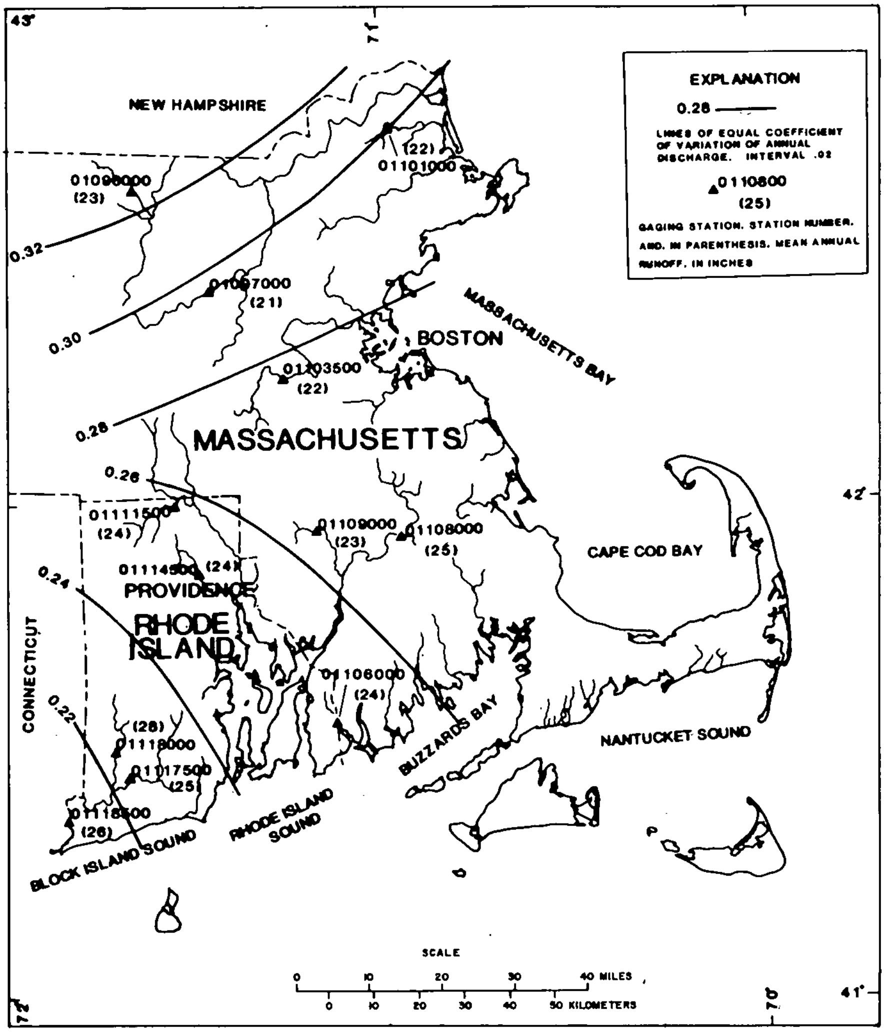

Figure 5: Map of eastern Massachusetts and Rhode Island showing location of gaging stations and lines of equal coefficient of variation of annual discharge.

the mean annual runoff when draft rate is equal to the mean annual discharge. The regionalized estimates of seasonal and carryover storage were thus combined and tabulated for chances of deficiency of 2, 5, and 10 percent in Tables 2, 3, and 4, respectively. Therefore, the estimates of storage requirements shown in these tables consider both seasonal and year to year variations in streamflow.

The use of Tables 2, 3, and 4 is illustrated by an example. Suppose a planner would like to know how much flow could be maintained with a 5 percent chance of deficiency by a proposed 1,000 million gallon (MG) (3.8 hm^3) reservoir with a water area of 0.75 mi^2 (1.9 km^2). The reservoir is to be located in the Taunton River basin midway between Boston and Providence at a site which drains 15 mi^2 (39 km^2). The planner might go through the following steps:

1) Estimate C_v of 0.26 from Figure 5.
2) Estimate the 7-day, 2-year low flow at the proposed site as 0.1 $ft^3s^{-1}mi^{-2}$ (1.1 $dm^3s^{-1}km^{-2}$) derived from information provided in Williams, Farrell, and Willey (1973).
3) Reduce storage to unit area basis — 1,000 MG/15 mi^2 = 67 MG/mi^2 (0.10 hm^3/km^2).
4) Table 3 indicates that such a reservoir would supply a draft rate of about 0.7 $ft^3s^{-1}mi^{-2}$ or 10.5 ft^3/s (0.3 m^3/s) with a 5 percent chance of deficiency.
5) Because draft rate is uncorrected for water losses due to changing land area to water area, these losses must be subtracted from draft rate to calculate the amount of flow can be maintained. The proposed reservoir would cover about 5 percent of the drainage basin. The Committee on Rainfall and Yield of Drainage Areas of the New England Water Works Association (1969) indicates a reduction in draft rate of about 0.06 $ft^3s^{-1}mi^{-2}$ (0.66 $dm^3s^{-1}km^{-2}$) would be appropriate, (Figure 6). Therefore, the flow that could be maintained from the proposed reservoir with a 5 percent chance of deficiency would be estimated as 9.6 ft^3/s (0.27 m^3/s).

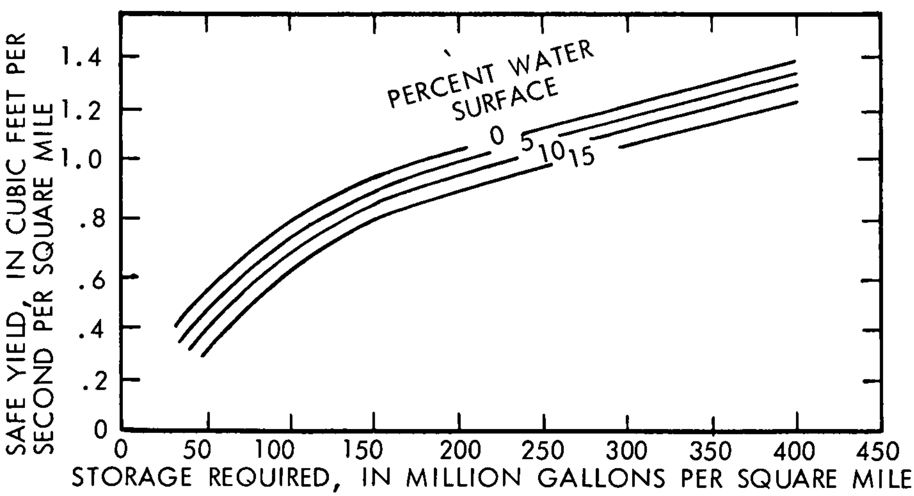

Figure 6: Yield of watersheds in New England. Based on composite data from Committee on Rainfall and Yield of Drainage Areas of the New England Water Works Association, 1969.

TABLE 2
TOTAL STORAGE REQUIREMENTS FOR
2 PERCENT CHANCE OF DEFICIENCY.

COEFFICIENT OF VARIATION (C_v)	MEAN ANNUAL RUNOFF (MAR), IN INCHES	7-DAY, 2-YEAR LOW FLOW, IN CUBIC FEET PER SECOND PER SQUARE MILE	STORAGE REQUIRED, IN MILLION GALLONS PER SQUARE MILE, TO MAINTAIN INDICATED DRAFT RATE						
			DRAFT RATE, IN CUBIC FEET PER SECOND PER SQUARE MILE						
			0.2	0.4	0.6	0.8	1.0	1.2	1.4
0.22	26	0.02	18	48	73	89	105	160	235
.22	26	.05	16	46	69	86	102	159	234
.22	26	.1	13	38	63	81	98	155	231
.22	26	.2	5	26	47	67	86	146	225
.22	26	.4	0	7	31	54	75	137	219
.24	25	.02	18	48	73	89	123	190	270
.24	25	.05	16	46	69	86	120	188	269
.24	25	.1	13	38	63	81	116	184	267
.24	25	.2	5	26	47	67	105	176	261
.24	25	.4	0	7	31	54	94	168	255
.26	23	.02	18	48	73	93	157	229	352
.26	23	.05	16	46	69	90	155	228	351
.26	23	.1	13	38	63	85	151	225	349
.26	23	.2	5	26	47	72	141	218	345
.26	23	.4	0	7	31	59	131	211	340
.28	22	.02	18	48	73	119	188	274	469
.28	22	.05	16	46	70	116	186	274	468
.28	22	.1	13	38	64	111	182	271	466
.28	22	.2	5	26	48	98	172	264	464
.28	22	.4	0	7	32	85	163	258	460
.30	22	.02	18	48	73	134	205	299	515
.30	22	.05	16	46	70	131	203	298	514
.30	22	.1	13	38	64	126	200	295	513
.30	22	.2	5	26	48	113	190	289	508
.30	22	.4	0	7	32	100	180	282	506
.32	22	.02	18	48	81	149	225	328	665
.32	22	.05	16	46	78	146	223	326	664
.32	22	.1	13	38	71	141	219	324	663
.32	22	.2	5	26	55	128	209	317	660
.32	22	.4	0	7	40	116	200	311	658

TABLE 3
TOTAL STORAGE REQUIREMENTS FOR 5 PERCENT CHANCE OF DEFICIENCY.

COEFFICIENT OF VARIATION (C_v)	MEAN ANNUAL RUNOFF (MAR), IN INCHES	7-DAY, 2-YEAR LOW FLOW, IN CUBIC FEET PER SECOND PER SQUARE MILE	STORAGE REQUIRED, IN MILLION GALLONS PER SQUARE MILE, TO MAINTAIN INDICATED DRAFT RATE						
			DRAFT RATE, IN CUBIC FEET PER SECOND PER SQUARE MILE						
			0.2	0.4	0.6	0.8	1.0	1.2	1.4
0.22	26	0.02	16	39	65	81	99	134	182
0.22	26	.05	13	38	63	80	99	134	182
0.22	26	.1	10	29	50	70	90	127	178
0.22	26	.2	3	15	40	60	82	120	172
0.22	26	.4	0	5	25	48	73	113	167
.24	25	.02	16	39	65	81	99	137	210
.24	25	.05	13	38	63	80	99	137	210
.24	25	.1	10	29	50	70	90	130	206
.24	25	.2	3	15	40	60	82	126	202
.24	25	.4	0	5	25	48	73	118	200
.26	23	.02	16	39	65	81	112	173	275
.26	23	.05	13	38	63	80	112	173	269
.26	23	.1	10	29	53	73	94	171	270
.26	23	.2	3	15	40	60	82	126	202
.26	23	.4	0	5	25	48	73	118	200
.28	22	.02	16	39	65	81	131	212	350
.28	22	.05	13	38	63	80	130	212	350
.28	22	.1	10	29	53	73	122	210	350
.28	22	.2	3	15	42	62	118	207	348
.28	22	.4	0	5	28	52	109	200	343
.30	22	.02	16	39	65	81	145	233	381
.30	22	.05	13	38	63	80	144	233	380
.30	22	.1	10	29	54	73	139	229	379
.30	22	.2	3	15	42	62	131	224	377
.30	22	.4	0	5	29	52	123	219	374
.32	22	.02	16	39	65	81	161	254	415
.32	22	.05	13	38	63	80	160	253	414
.32	22	.1	10	29	54	73	155	250	413
.32	22	.2	3	15	42	62	147	244	411
.32	22	.4	0	5	29	52	139	240	407

TABLE 4
TOTAL STORAGE REQUIREMENTS FOR 10 PERCENT CHANCE OF DEFICIENCY.

COEFFICIENT OF VARIATION (C_v)	MEAN ANNUAL RUNOFF (MAR), IN INCHES	7-DAY, 2-YEAR LOW FLOW, IN CUBIC FEET PER SECOND PER SQUARE MILE	STORAGE REQUIRED, IN MILLION GALLONS PER SQUARE MILE, TO MAINTAIN INDICATED DRAFT RATE — DRAFT RATE, IN CUBIC FEET PER SECOND PER SQUARE MILE: 0.2	0.4	0.6	0.8	1.0	1.2	1.4
0.22	26	0.02	15	35	62	79	97	116	151
.22	26	.05	10	30	56	74	92	113	148
.22	26	.1	6	25	47	67	86	108	145
.22	26	.2	2	14	35	56	77	101	140
.22	26	.4	0	3	22	45	68	94	135
.24	25	.02	15	35	62	78	97	118	168
.24	25	.05	10	30	56	74	93	114	166
.24	25	.1	6	25	47	66	87	110	162
.24	25	.2	2	14	35	56	78	104	158
.24	25	.4	0	3	22	45	70	97	154
.26	23	.02	15	35	62	79	98	131	221
.26	23	.05	10	30	56	74	94	128	219
.26	23	.1	6	25	47	67	88	123	218
.26	23	.2	2	14	35	57	80	118	214
.26	23	.4	0	3	22	47	73	112	211
.28	22	.02	15	35	62	79	103	166	277
.28	22	.05	10	30	56	74	99	164	277
.28	22	.1	6	25	47	67	94	160	274
.28	22	.2	2	14	35	58	87	155	272
.28	22	.4	0	3	23	48	79	150	269
.30	22	.02	15	35	62	79	107	182	301
.30	22	.05	10	30	56	74	103	179	298
.30	22	.1	6	25	47	67	98	175	295
.30	22	.2	2	14	35	58	90	171	293
.30	22	.4	0	3	23	48	83	165	289
.32	22	.02	15	35	62	79	116	211	330
.32	22	.05	10	30	56	74	112	209	328
.32	22	.1	6	25	47	67	107	205	326
.32	22	.2	2	14	35	58	100	200	325
.32	22	.4	0	3	23	48	95	196	322

Discussion

The probability routing method of computing carryover storage assumes the annual discharges are independent events. If annual discharges are autocorrelated (not independent), lower draft rates than indicated in Tables 2, 3, and 4 will result. Hardison (1966) points out that draft rates at the upper end of the draft-storage relations should be reduced by about 5 percent of the mean annual discharge when the first order serial correlation coefficient of annual discharge is 0.2. The serial correlation coefficients shown in Table 1 indicate possible autocorrelation in annual discharges for streams in eastern Massachusetts and Rhode Island. Although the period of record for these stations is not long enough to compute reliable serial correlation coefficients, there may be some justification for reducing by 0.1 $ft^3s^{-1}mi^{-2}$ (1.1 $dm^3s^{-1}km^{-2}$) indicated draft rates of 1.0 $ft^3s^{-1}mi^{-2}$ (11 $dm^3s^{-1}km^{-2}$) or more in Tables 2, 3, and 4.

The draft-storage relations presented here are based only on hydrologic considerations. It may not be feasible to provide the amount of storage indicated by the relations because of unsuitable physical characteristics of the storage site. The Committee on Rainfall and Yield of Drainage Areas of the New England Water Works Association (1969, pages 168-169) does not consider it economically feasible in New England to increase storage much beyond 200 MG/mi^2 (0.3 hm^3 /km^2) of watershed.

Definitions

The following definitions are used:

Draft rate is gross reservoir outflow; uncorrected for water losses due to changing land area to water area (evaporation and seepage). That portion of *draft rate* assigned to water losses must be evaluated as specific features of the reservoir site.

Percent chance of deficiency is the percent of years within which a storage reservoir of indicated capacity would become empty. For example, if for a certain *draft rate* a reservoir has a 10 *percent chance of deficiency,* then the reservoir could be expected to not fully supply that *draft rate* an average of 1 year in 10. It does not imply that the chance of a reservoir becoming empty is equally probable each year. The chance of a reservoir becoming empty during a year following a series of dry years which left the reservoir nearly empty would be greater than indicated in this analysis.

Storage required is the usable volume of a reservoir available to maintain the indicated *draft rate.*

7-day, 2-year low flow is the annual minimum 7-day average flow at the 2-year recurrence interval in cubic feet per second per square mile or cubic decimetres per second per square kilometre.

Coefficient of variation is standard deviation divided by mean.

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