Storage-Reliability-Resilience-Yield Relations for Northeastern United States

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Abstract: An evaluation of time-series of streamflow at 166 basins in the northeastern United States reveals that this region is remarkably homogeneous in terms of the year-to-year variability and persistence of average annual streamflow. Goodness-of-fit tests reveal that the 166 time-series of annual streamflow tested were well approximated by a lag-one normally distributed autoregressive process with a fixed lag-one correlation and a fixed coefficient of variation. Computer experiments revealed that the observed variability about these fixed values could easily arise from sampling alone, due to the varied and short records available. Recent research on the behavior of water supply systems reveals that simple analytic models can describe the general relationships among reservoir storage, yield, reliability, and resilience for systems dominated by overyear storage requirements. An analytic storage model is combined with the regional model of annual streamflow, resulting in general relations among storage, reliability, yield, and resilience useful for water supply systems in the Northeast. An example using the water supply systems for New York City, Boston, Providence, Rhode Island, and Springfield, Massachusetts, documents how the proposed methodology may be used to compare the behavior of four very different systems.

INTRODUCTION

The primary function of most water supply systems is as a defense against drought. In the context of water supply management, drought is a very complex concept that depends on hydroclimatologic characteristics associated with the watersheds that service the reservoirs, reservoir storage capacities, reservoir operating rules, and system demands. Recent pervasive and episodic drought experiences in the United States led Congress to request the Army Corps of Engineers (under its mandate by the Water Resources Development Act of 1986) to coordinate a national study of water management during drought ("National" 1991). This study led to detailed drought preparedness studies for several individual river basins and a "National Drought Atlas" that provides a statistical summary of various important climatic characteristics across the nation. Yet still, we are left with the question of how well prepared one water-supply system is compared to another in defense against drought. Which water supply systems are most vulnerable to major water supply failure in a particular region? What characteristics make one water supply system more vulnerable or more resilient to drought than a neighboring system? To answer these and other questions one needs to integrate the effects of hydroclimatologic characteristics, reservoir system storage capacity, operating rules, and system yield in a systematic manner. This study develops an integrated yet simple approach for comparing the reliability, resilience, vulnerability, and overall system behavior for water supply systems in the northeastern United States. The methodology described here could be extended to other regions.

A complete analysis of a complex water supply system often requires months or years of data collection and model formulation leading ultimately to the simulation and possibly optimization of the behavior of the overall water supply system. Historically, one modeling approach has been succeeded by, or appended to, another more complex one to deal with "new" issues such as the Hurst phenomenon, model parameter uncertainty, optimal operations, spatial and temporal dissaggregation schemes for stochastic streamflow generation, and object-oriented programming. With the rapid development of computer technology and software, our tools for analysis are becoming more user friendly and powerful, making it much easier to develop models that describe the behavior of complex water supply systems. What is still lacking are simple, reasonably accurate "back-of-the-envelope" methods that give insight into a wide range of water supply system behavior before one embarks on a complex modeling expedition. Such a simple modeling framework also offers the potential for developing meaningful measures of water supply system performance.

This study develops generalized relationships among storage, yield, reliability, resilience, and drainage area, which can be used in preliminary investigations of overall water supply system behavior in the northeastern United States. The resulting relationships can lead, in a few minutes, to approximate yet general statements about the behavior of an individual water supply system. The methodology is particularly useful for very large and complex systems that contain many individual storage reservoirs that are connected in both series and parallel. To demonstrate the usefulness of the suggested methodology, the relationships developed here are applied to the water supply systems that service New York City, Boston, Providence, Rhode Island, Springfield, Massachusetts. These case studies illustrate how regional storage-reliability-resilience-yield (SRRY) relationships can be used for comparing the responses of alternative water supply systems to drought.

REGIONAL HYDROLOGIC MODELS FOR NORTHEASTERN UNITED STATES

The behavior of water supply systems is dictated, in part, by the behavior of the streamflow that enters the system from its associated watershed(s). In this section we describe computer experiments that document the overall homogeneity of annual streamflow in the northeastern United States.

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Hydrologic Database

The U.S. Geological Survey (USGS) recently developed a database of streamflow records for 1,659 streamflow gages in the United States that is suitable for use in hydroclimatic investigations (Slack and Landwehr 1993). This study uses 166 of those streamflow records located in the northeastern United States, as illustrated in Fig. 1. Here a water year begins October 1 and ends September 30. All the records have at least a "good" rating for the record of daily mean discharges used to estimate annual average streamflow. The USGS applies a good rating if 95% of the daily discharges are within 10% of their true value. The 166 basins chosen for use in this study have record lengths that range from 19 to 86 years, with an average record length of 48 years.

Evaluation of Potential Trends in Annual Streamflow

Our analysis assumes that the streamflows are unregulated and largely unaffected by anthropogenic influences. It is for this reason that we use a subset of the USGS Hydro-Climatic Data Network (HCDN) (Slack and Landwehr 1993) that was designed specifically for studies of this kind. The USGS HCDN only contains streamflow data for basins in which there has been no obvious adjustment of "natural" streamflow through hydraulic diversions and/or regulation. Although the hydrology of these basins may be subject to some degree of anthropogenic influence such as land-use changes, we hypothesize that the effects are not discernable using annual streamflow data. To test this hypothesis, the 166 time-series of streamflow were evaluated to determine whether any temporal trends in average annual streamflow were evident. Two tests were performed; a first-order linear regression approach to test for a linear trend and a Mann-Kendall test to evaluate both linear and nonlinear trends. Both of these tests are described by Helsel and Hirsch (1992, Chapter 12).

The linear regression approach uses a t-test to determine whether or not there is a significant linear relationship between average annual streamflow and time. Of the 166 streamflow records tested, 10 sites failed the linear regression trend test (t-test) and 10 sites failed the nonparametric Mann-Kendall test using a significance level of 5%. If our null hypothesis that the 166 time-series had neither a linear nor nonlinear trend was correct, one would expect 0.05(166) = 8 rejections or failures. These results suggest that there is a strong possibility that those 10 sites that failed the hypothesis tests, did so simply by chance, the result of type I errors, where the null hypothesis is mistakenly rejected. Therefore we conclude that this database of average annual streamflows does not exhibit significant temporal trends. Similar results were reported by Lins and Michaels (1994) for monthly streamflows in this region. Lins and Michaels reported statistically significant trends in monthly streamflow for this region during only one out of 12 months. Such results would be expected to occur by chance alone, when using a significance level of approximately 1/12.

Probability Distribution of Annual Streamflows

L-Moment Diagrams

Recent research (Hosking 1990; Hosking and Wallis 1993; and Vogel and Fennessey 1993) has shown that L-moment diagrams provide one of the simplest and most convincing procedures for evaluating the goodness-of-fit of alternative probability distributions to regional sets of hydroclimatic data. Since the theory (Hosking 1990; Hosking and Wallis 1993) and application (Hosking 1990; Hosking and Wallis 1993; and Stedinger et al. 1993) of L-moment diagrams for evaluating the goodness-of-fit of alternative distributions is discussed elsewhere, we only document our results here.

Fig. 2 illustrates the relationship between L-coefficient of variation (L-C_V) and L-skewness for the 166 observed time-series of annual streamflow. For comparison, the theoretical relationship between L-C_V and L-skewness is shown for the gamma, lognormal, and normal distributions, along with the regional mean value of the observed L-moments. Unfortunately none of the three theoretical models evaluated coincide exactly with the regional mean of the L-moments, shown using a large closed circle. We only evaluate these three theoretical models, because the generalized analytic SRRY relationships for storage reservoirs, used later on, are currently only available for reservoir systems fed by correlated normal, lognormal, or gamma distributed annual streamflows. Fig. 2 indicates that of these three models, the normal and gamma models provide the best fit overall.

Hosking (1990) provides a hypothesis test for normality against skewed alternatives that is based on the sample L-moment ratio termed L-skewness τ_3. Hosking proposed the use of the test statistic $N_n = \tau_3(0.1866n^{-1} + 0.8n^{-2})^{-1/2}$ where τ_3 is the sample L-skewness, n is the sample size, and N_n follows a standard normal distribution. Using a 5% significance level, we had to reject normality for 19 of the 166 sites (11% of the sites) using this test. This is roughly twice

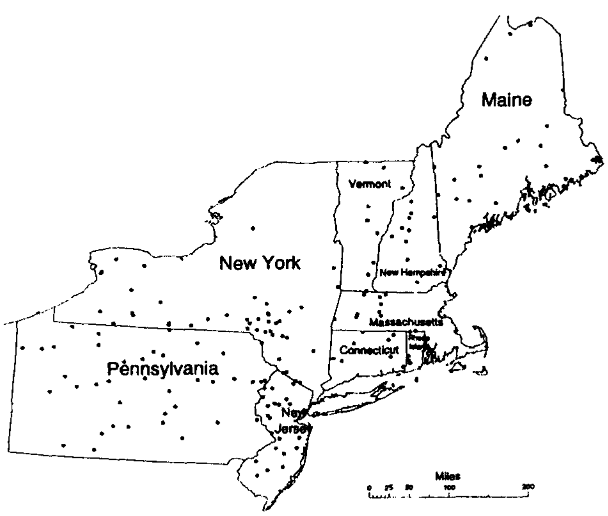

FIG. 1. Study Region Including Location of 166 USGS Stream-Gauging Stations

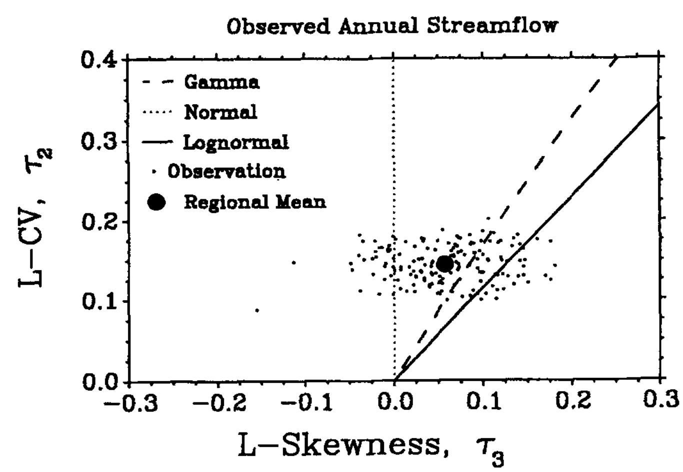

FIG. 2. L-Moment Diagram Illustrating Relationship between L-Coefficient of Variation and L-Skewness for Observed Annual Streamflows

as many rejections as would be anticipated under the null hypothesis. Clearly there is some evidence of nonnormality, yet for practical purposes, the annual streamflows appear well approximated by a normal distribution at most of the sites, because we could not reject the null hypothesis of normality at 166 − 19 = 147 of the sites, using a 5% significance level L-skewness test. This issue is addressed again in the following.

Regional Probability Plot Correlation Coefficient Hypothesis Tests

Vogel and Kroll (1989) and Stedinger et al. (1993) describe the use of the probability plot correlation coefficient (PPCC) hypothesis test for single samples, and Vogel and Kroll (1989) show how to extend those hypothesis tests to regional samples. In this case, a normal PPCC hypothesis test was performed for each of the 166 samples and in each case, the at-site significance level a was computed. Significance levels were derived by interpolation of tables developed by Looney and Gulledge (1985). In theory, each set of 166 computed significance levels should be uniformly distributed across space. That is, if the flows were actually normally distributed, one *would* obtain a uniform distribution of significance levels. Hence, a regional lognormal PPCC test can be performed by constructing a uniform probability plot of the significance levels associated with each of the flow series as shown in Fig. 3. Clearly, the distribution of significance levels approaches a uniform distribution as is expected. In theory, the mean and standard deviation of a uniformly distributed random variable are 0.5 and 0.289, respectively. As shown in Fig. 3 we obtained an average and standard deviation of the significance levels equal to 0.489 and 0.315, respectively. These results document that a normal distribution provides an excellent approximation to the distribution of annual streamflows in this region, and since the theory of storage reservoir behavior is particularly well defined and understood for normally distributed inflows, we chose the normal distribution to model streamflows here. A validation experiment performed later on provides additional evidence of normality.

Other portions of the United States will likely require other distributional assumptions. For example, Markovic (1965) showed that annual streamflows at 446 sites in the western United States were well approximated by both lognormal and gamma distributions at 446 sites, whereas the normal distribution did not perform as well there. Similarly Löf and Hardison (1966, Table 1) concluded that annual streamflows in eight out of 22 water resource regions in the United States (including New England) were well approximated by a normal distribution, whereas a lognormal or Weibull distribution was required in the remaining basins.

Regional Hydrologic Relationships

Regional hydrologic studies seek to develop relationships between streamflow characteristics and easily determined watershed characteristics. As is illustrated in Stedinger et al. (1993, Figure 18.5.1), regional hydrologic models for average annual or even average monthly streamflow volumes are much more precise than regional models for flood-flow or low-flow volumes. Since the present study only focuses on the year-to-year or overyear behavior of water supply systems, we concentrate on regional hydrologic models for annual average streamflow volumes.

Regional Hydrologic Models for Mean Annual Streamflow μ

Fig. 4 documents the remarkably good relationship between observed average annual streamflow volumes μ in millions of gallons per day (mgd) (1 mgd = 0.0438 m^3/s), versus drainage area A in square miles (1 sq mi = 2.59 km^2), for the 166 watersheds illustrated in Fig. 1. Ordinary least squares regression procedures produced the model

$$\mu = 1.17A^{0.985} \tag{1}$$

with an adjusted R^2 = 98.5. Similar regional models of annual average runoff could be developed for other regions of the United States. It is possible to obtain improvements to (1) by including other explanatory variables that act as surrogates for climatic and geohydrologic influences. For example, the model

$$\mu = 0.091A^{0.987}H^{0.092}T^{-0.752}P^{1.31} \tag{2}$$

where μ = average annual streamflow in mgd, (1 mgd = 0.0438 m^3/s); A = drainage area in sq mi; H = basin relief in ft, (1 foot = 0.3048 m); T = average annual temperature in °F; and P = average annual precipitation in inches, (1 in. = 2.54 cm), is a significant improvement over (1) with an adjusted R^2 = 99.1. Basin relief is defined here as the difference between the average basin elevation and the elevation of the streamgauge at the outlet of the basin. All model parameter estimates in (1) and (2) are significantly different from zero using a 1% level significance test and the residuals in both models were well approximated by a normal distribution.

In addition to yielding significantly more accurate estimates

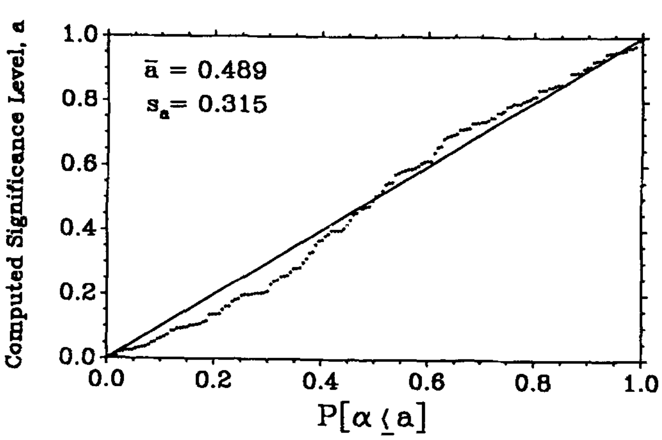

FIG. 3. Regional Uniform Probability Plot Illustrating Distribution of Significance Levels of 166 Normal Probability Plot Correlation Coefficient Hypothesis Tests

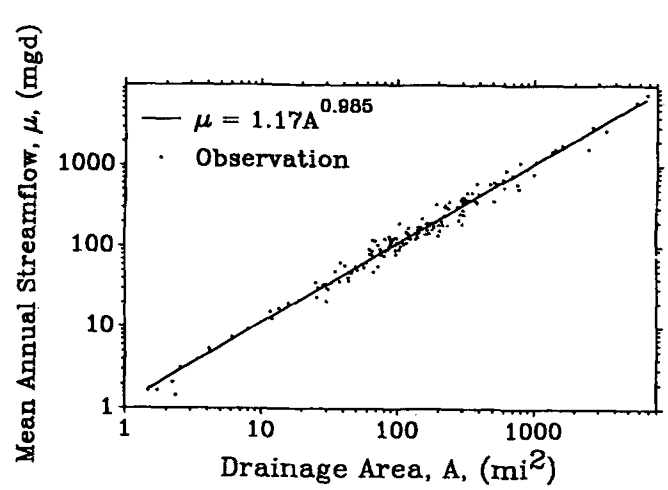

FIG. 4. Observed Annual Average Streamflow versus Drainage Area

of μ, (2) allows for an evaluation of the impact of changes in temperature and precipitation on basin runoff and thus water supply for this region. Eq. (2) is analogous to the graphical relations developed by Langbein et al. (1949), because it allows us to quantify the increases in average annual runoff that result from either increases in annual average precipitation or decreases in annual average temperature.

Regional Hydrologic Model for C_V and ρ

Fig. 5(a) illustrates estimates of the coefficient of variation C_V and the lag-one serial correlation coefficient ρ of annual average streamflow for each of the 166 sites. Since all estimates of C_V and ρ in Fig. 5(a) contain significant sampling variability due to the often short and varied length of records across sites, we hypothesize that the relatively uniform scatter shown in Fig. 5(a) about the regional mean values of C_V = 0.25 and ρ = 0.19 could be due to statistical sampling alone. This hypothesis is tested in the next section.

Our use of regional mean values for the statistics C_V and ρ is very similar to the assumptions made in previous national evaluations of water supply development by Löf and Hardison (1966) and Hardison (1972). For example, on the basis of annual streamflow records for 180 basins in the United States, Löf and Hardison (1966) document that the average lag-one correlation was ρ = 0.17, as compared with the average value of ρ = 0.19 used in this study. Similarly, Hardison (1972, Table 2) documents that the average coefficient of variation of annual streamflows in the North Atlantic regions was C_V = 0.19, as compared with the average value of C_V = 0.25 used in the present study. Interestingly, Hardison (1972, Table 2) documents values of C_V for 17 regions in the United States, with an average value of 0.35, a minimum value of 0.19 for the North Atlantic region, and a maximum value of 0.77 for the Lower Colorado region.

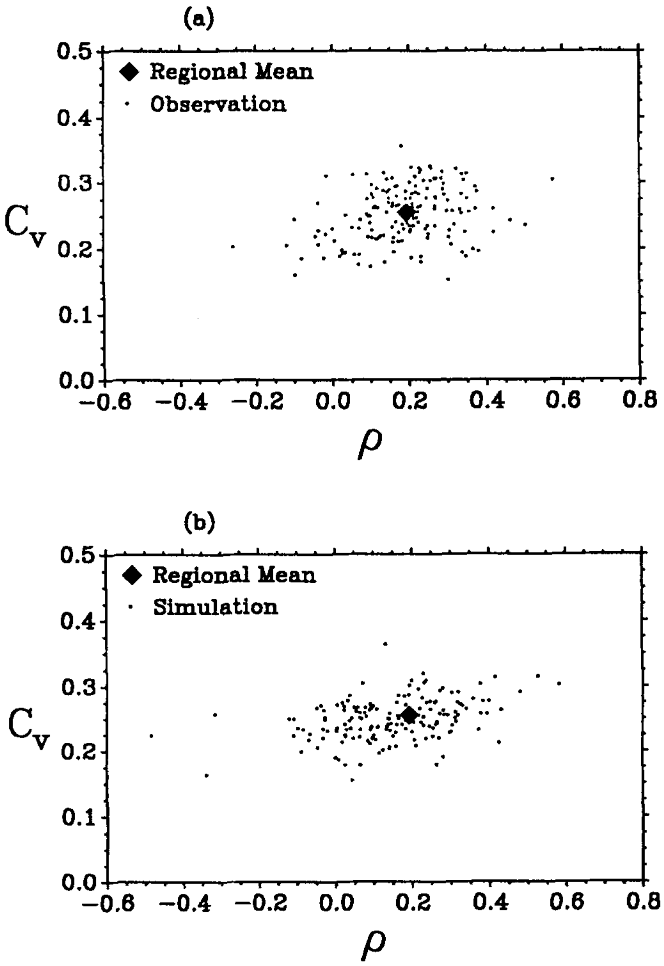

FIG. 5. Estimates of Coefficient of Variation C_V versus Lag-One Serial Correlation ρ of: (a) Observed Annual Streamflows; and (b) Synthetic Annual Streamflows

For other regions of the United States in which values of C_V are larger, L-moment diagrams should be used to evaluate both the year-to-year variability and the persistence of annual streamflows, because the statistics C_V and ρ exhibit significant bias for short skewed samples as is proven by Vogel and Fennessey (1993).

Regional Hydrologic Model Validation

To test our hypotheses that average annual streamflows in this region can be approximated by a normal distribution and a lag-one autoregressive model with constant C_V = 0.25 and constant lag-one serial correlation ρ = 0.19, we perform an experiment and several hypothesis tests. We generated 166 independent sets of synthetic normally distributed annual streamflow traces from a lag-one autoregressive model with constant C_V = 0.25 and constant lag-one serial correlation coefficient ρ = 0.19. To mimic the 166 observed annual flow series as closely as possible, each synthetic streamflow trace was generated with a record length equal to one of the record lengths of the 166 observed average annual flow series.

The results of the validation experiment are illustrated in Fig. 5(b). Fig. 5(b) reports estimates of C_V and ρ for the 166 synthetic annual streamflow series along with the regional mean of the synthetic flows. Naturally, the regional mean of the synthetic annual flows are approximately equal to the assumed regional mean values C_V = 0.25 and ρ = 0.19. This result would not occur if the flow traces were highly skewed, because the ratio estimators of C_V and ρ are known to exhibit significant bias for skewed samples [see Vogel and Fennessey (1993)]. The important feature of Fig. 5(b) is that the scatter about the regional mean values of C_V and ρ associated with the synthetic streamflows is very similar to the scatter illustrated earlier in Fig. 5(a) for the observed average annual flows. Since we constructed the experiment assuming fixed values of C_V and ρ, all of the scatter about the regional mean values of C_V and ρ in Fig. 5(b) is due to statistical sampling, alone. Therefore we conclude that most of the scatter reported earlier in Fig. 5(a) is probably due to statistical sampling alone and it makes reasonably good sense to assume that the coefficient of variation and the lag-one serial correlation of average annual streamflow are fixed for this region at 0.25 and 0.19, respectively. The regional hydrologic model for the northeastern United States can now be summarized by $\mu = 1.17A^{0.985}$ with C_V = 0.25 and ρ = 0.19. One could replace (1) with (2) to obtain more accurate results.

To test our assumption that the regional hydrologic model provides a good approximation to the distribution of average annual streamflow for this region, we provide an L-moment diagram summarizing the 166 synthetic flow traces in Fig. 6. Again the scatter shown in the L-moment diagram for the observed streamflows in Fig. 2 is very similar to the scatter shown for the synthetic streamflows in Fig. 6. This experiment demonstrates, again, that synthetic annual streamflows generated from a lag-one autoregressive normal model with fixed C_V = 0.25 and ρ = 0.19 appear to reproduce, approximately, the character of the observed annual streamflow data for this region. Naturally, other regional time-series models would be required for other regions of the United States.

The results of our simulation experiment summarized in Figs. 5 and 6 provide only qualitative assessment of our hypothesis of fixed values for the statistics C_V, ρ, L-C_v and L-skewness in this region. To make the assessment more quantitative and rigorous two additional tests are used.

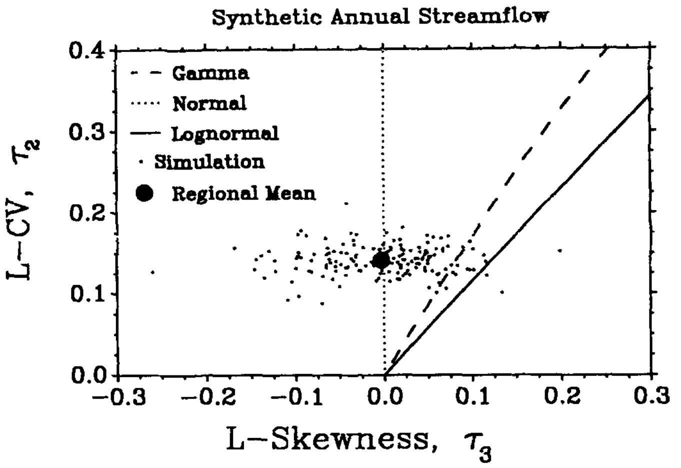

FIG. 6. L-Moment Diagram Illustrating Relationship between L-Coefficient of Variation and L-Skewness for Synthetic Annual Streamflows

In a regional analysis of water supply in eastern Massachusetts and Rhode Island, Tasker (1974) found that C_V appeared to be related to geographic location, hence he provided a map of C_V. To test whether C_V and ρ depend upon other factors, we attempted to fit multivariate regression equations between both C_V and ρ, and numerous basin characteristics including drainage area, gauge elevation, channel slope, stream length, mean basin elevation, Soil Conservation Service (SCS) soil infiltration index, basin relief, basin latitude, and basin longitude. No significant relationships could be discerned using a 5% level F-test, hence we concluded that both C_V and ρ are not correlated with basin size, shape, or location.

To evaluate whether both the observed annual flow series, and the synthetic annual flow series, are characterized by a fixed coefficient of variation and skewness, rank-sum tests are performed on the sample values of L-C_V and L-skewness derived from both the observed and the synthetic samples. Essentially, we are asking whether or not the 166 observed and synthetically generated values of L-C_V and L-skewness, illustrated in Figs. 2 and 6 could have come from the same population. The rank-sum test, also known as the Wilcoxon rank-sum test and the Mann-Whitney test, is described by Helsel and Hirsch (1992). It is a nonparametric test, which in this case makes no assumptions about the distributional properties of the sample statistics L-C_V and L-skewness. Using the large-sample version of this test with corrections for ties, described by Helsel and Hirsch (1992), the p-values for two-sided rank-sum tests on L-C_V and L-skewness were 0.15 and 0.20, respectively. Therefore, there is ample evidence to accept the null hypothesis that both the observed and synthetically generated values of L-C_V and L-skewness could have originated from the same population.

REGIONAL STORAGE-RELIABILITY-RESILIENCE-YIELD RELATIONSHIPS

A regional model that relates storage, yield, and reliability requires a regional hydrologic model for the inflows to the water supply system in combination with the repetitive application of reservoir routing and stochastic streamflow models to define the SRRY relationship at each site in the defined region.

Review of Previous Regional Storage-Reliability-Yield Relations

Two different approaches are usually taken in the development of regional storage-reliability-yield (SRY) relations. One approach, which has been the most useful to practicing engineers, is to develop empirical storage-yield relationships for selected basins in a region. For example, after the New England droughts of 1908–1914, 1929–1935, 1939–1941, and 1961–1967, the Committee on Rainfall and Yield of Drainage Areas of the New England Water Works Association (NEWWA) published curves describing the relationships between storage and yield in the December 1914, September 1945, and June 1969 editions of the *Journal of the NEWWA* ("Progress" 1969). Those curves, termed the NEWWA curves, are reproduced later on in this study.

In the United States most empirical storage-yield curves were derived by routing historical monthly streamflows for a particular river basin through a suite of hypothetical storage reservoirs and applying Rippl's (1883) mass curve or its automated equivalent sequent peak algorithm [see Loucks et al. (1981)]. The application of the mass-curve approach leads to the minimum storage capacity that would deliver the prespecified yield, without failure, during the historical period of record. Such analyses do not provide information about the frequency of failures or the overall system reliability because those methods do not allow the reservoir system to fail. Other methods such as behavior analysis and probability routing methods are more useful for investigating frequency of failures and overall system reliability [see McMahon and Mein (1986)]. Vogel and Bolognese (1995) provide a review of the different interpretations of reservoir system reliability used in the United States and elsewhere.

Löf and Hardison (1966), Hardison (1972), Tasker (1974), Haktanir (1984), and others developed regional storage-yield relations that account for the reliability of the yield. Löf and Hardison (1966), Hardison (1972), and Tasker (1974) used probability routing methods [see McMahon and Mein (1986)] that determine the steady-state probability associated with each desired release target. Probability routing methods have seen limited use in the United States for the design and operation of storage reservoirs, although they have been used widely elsewhere.

Tasker's (1974) SRY relationships for eastern Massachusetts and Rhode Island are simple to implement because they only require a map of the coefficient of variation of annual streamflow in combination with estimates of the 7-day, 2-year low flow and the drainage area of the proposed site.

Löf and Hardison (1966) and Hardison (1972) developed SRY curves for the entire nation for the purpose of determining future levels of development, given the current inventory of storage reservoirs and the potential future (rising) cost of water. Their analysis, similar to this study, is based on fitting a suitable probability distribution to the annual streamflows in a region, assuming a fixed value of C_V for that region and deriving a SRY relationship using probability routing methods. The resulting overyear SRY relations are corrected to include within-year storage requirements using a method introduced by Beard (1964) and corrected for the serial correlation of annual streamflows using a method introduced by Hardison (1966).

A second and promising approach to the development of regional SRY relations is to use stochastic streamflow models in combination with the sequent peak algorithm to derive general relationships between system storage, reliability, resilience, and system yield. Although such procedures are usually used for the simulation of individual water supply systems, they could be generalized to apply to *all* water supply systems. Recent research on the theory of storage reservoir system behavior has produced very general relationships between reservoir system storage, reliability, resilience, and yield. Vogel and Bolognese (1995), Buchberger and Maidment (1989), Vogel and Stedinger (1987), Klemes (1987), and others cited therein, provide recent reviews of the literature on generalized SRY relationships. Unfortunately these general theoretical relationships come at the expense of only being useful for reservoir systems that are dominated by overyear, or carryover storage requirements. This study concentrates on overyear or carryover storage requirements; however, it is possible to extend this study to include seasonal storage requirements using methods introduced by Beard (1964), Löf and Hardison (1966), Hardison (1972), and Riggs and Hardison (1973). For example, Löf and Hardison (1966), Hardison (1972) and Riggs and Hardison (1973) show how to estimate total storage requirements by adding a seasonal (within-year) adjustment to the carryover (overyear) storage requirements.

A review of the literature reveals that most general SRRY relationships have been developed by, and for the benefit of, theoretical investigations into storage reservoir behavior or for very general assessments of the U.S. water supply with little applicability to actual reservoir systems. However, Vogel and Hellstrom (1988) showed that analytic SRY relationships can provide very detailed and useful practical information regarding storage reservoir behavior for a system dominated by carryover storage, such as the Quabbin-Wachusett reservoir system, which services eastern Massachusetts. Furthermore, Löf and Hardison (1966) and Hardison (1972) demonstrate quite clearly, that as the marginal cost of water increases, levels of development tend to increase, leading to increased overyear storage requirements. As levels of development increase, the type of analysis described here should become increasingly important.

Measures of Reservoir System Resilience

The concept of resilience was introduced to the water resources literature by Matalas and Fiering (1977) and has subsequently been discussed and defined in a number of different ways. Hashimoto et al. (1982) define resilience as the likelihood that a system will recover from a failure once a failure has set in. We exploit that notion of resilience here.

Hazen (1914) introduced an index of reservoir system performance defined as

$$m = \frac{(1 - \alpha)\mu}{\sigma} = \frac{(1 - \alpha)}{C_V} \tag{3}$$

where α = average annual system demand or yield as a fraction of the mean annual inflow μ to the system; σ = standard deviation of the annual inflows; and $C_V = \sigma/\mu$ is the coefficient of variation of the annual inflows. Vogel and Bolognese (1995) review the use of the index m in previous studies. In general, systems with significant carryover storage requirements exhibit a value in the range $0 < m < 1$, whereas systems with predominantly seasonal storage requirements exhibit a value of $m > 1$. Therefore, the index m is proportional to the resilience of the system because resilient systems tend to refill very quickly after emptied, which is exactly what happens to systems dominated by seasonal storage requirements ($m > 1$). Similarly, small values of m ($m < 1$), correspond to systems with low resilience because they are dominated by carryover storage requirements; such systems may take years, or even decades to refill. Using this reasoning, Vogel and Bolognese (1995) termed m the resilience index. Combining (3) with the regional hydrologic model $C_V = 0.25$ leads to $m = 4(1 - \alpha)$, so reservoir systems in the northeastern United States with levels of development α significantly in excess of 0.75 will be dominated by carryover storage requirements, whereas systems with α significantly lower than 0.75 will be dominated by seasonal storage requirements.

Following Hasimoto et al. (1982) one may define an index of resilience r as the conditional probability that a reservoir system recovers from a failure after a failure has set in. Here a failure is defined as the inability of the reservoir system to provide the target yield. Vogel and Bolognese (1995) show that for systems fed by lag-one autoregressive normally distributed streamflows, as is the case for systems in the northeastern United States, one may approximate r using

$$r = \Phi\left[\frac{m - \dfrac{\rho(2\pi)^{-1/2}}{\Phi(-m)\exp(m^2/2)}}{\sqrt{1 - \rho^2}}\right] \tag{4}$$

where ρ = the lag-one serial correlation coefficient of the inflows; m is defined in (3); and Φ denotes the cumulative probability distribution operator for a standardized normal random variable. Note that for independent inflows ($\rho = 0$) the resilience index r reduces to $r = \Phi(m)$ so that the resilience of an infinite reservoir ($m = 0$) is 0.5. Vogel (1987) and Vogel and Bolognese (1995) document that r is one of the two parameters in a two-state Markov model of reservoir system states that they verify is useful and accurate for evaluating the conditional behavior of systems dominated by both within-year and overyear storage requirements, respectively.

Regional Storage-Reliability-Resilience-Yield Model for Northeastern United States

The goal of this study is to combine a general analytic model that describes the relationships among carryover storage, reliability, resilience, and yield with the regional hydrologic streamflow model developed earlier for the northeastern United States. For this task, an analytic model is required that describes the relationships among the reservoir system storage, reliability, and yield for systems fed by lag-one autoregressive normally distributed inflows. Pegram (1980) and Buchberger and Maidment (1989) report general relationships between storage capacity, steady-state probability of a failure q and resilience index m for systems fed by independent ($\rho = 0$) normal inflows. Pegram's relations are in tabular form so they are not completely general. One could use Buchberger and Maidment's (1989) analytic model, adding the correction for serial correlation derived by Phatarfod (1986); however, Phatarfod's correction factor was shown to be only very approximate in this instance (Vogel and Bolognese 1995). To our knowledge, the only general analytic relationships available for AR(1) normal inflows are those developed by Vogel (1985) and reported in the appendix to Vogel and Bolognese (1995). Those relationships are sets of multivariate regression equations that relate the storage capacity S to resilience index m, lag-one serial correlation coefficient of the inflows ρ, and probability p, of no-failure reservoir system operations over and N-year planning period. The multivariate relationships were developed from Monte Carlo experiments that routed AR(1) normal inflows through a wide class of reservoir systems using the sequent peak algorithm. The use of these approximations are equivalent to having performed stochastic simulation experiments of the type described by Vogel and Stedinger (1987), Vogel and Hellstrom (1988), McMahon and Mein (1986), and many others cited therein. The multivariate regression equations for AR(1) normal inflows were developed using exactly the same procedures as the regression equations developed for AR(1) lognormal inflow described by Vogel and Stedinger (1987).

Reservoir System Reliability

Two schools of thought exist regarding the reliability of water supply systems. In the United States, system reliability is often defined as the probability of no-failure reservoir operations p, over an N-year planning period, since that is what is simulated using Rippl's (1883) mass curve approach or its automated equivalent sequent peak algorithm. This is because Rippl's mass curve, or its automated equivalent, leads to the minimum reservoir storage capacity that can just deliver a prespecified yield, without failure, over the period of record used in the simulation. Elsewhere, failures are allowed in the simulations and system reliability is often defined in terms of the steady-state probability of a system failure q. Vogel (1987) and Vogel and Bolognese (1995) show that these two definitions of system reliability p and $(1 - q)$ can be related using

$$p = (1 - q)\left[1 - \frac{rq}{1 - q}\right]^{N-1} \tag{5}$$

where p = no-failure system reliability over an N-year planning period; q = steady-state probability of a failure; and r = system resilience estimated and defined in (4). Vogel (1987) and Vogel and Bolognese (1995) show that (5), which is based on a two-state Markov model of reservoir system states, provides a very good approximation to the relationship between p and q as long as $m > 0.2$. In this study, water supply system reliability is always defined as the steady-state system reliability 1-q. We prefer the interpretation of steady-state system reliability 1-q, over no-failure reliability p, because one's interpretation of the steady-state system reliability does not depend on the length of the planning period.

REGIONAL STORAGE-RELIABILITY-RESILIENCE-YIELD CURVES FOR NORTHEASTERN UNITED STATES

Combining the regional AR(1) normal hydrologic model for the northeastern United States with (3)–(5) and the generalized analytic SRY relations in Vogel (1985) and Vogel and Bolognese (1995) led to the general regional SRRY curves illustrated in Fig. 7. Here reliability is defined as the steady-state system reliability, 1-q, described in (5) and discussed in detail by Vogel and Bolognese (1995). The curves in Fig. 7

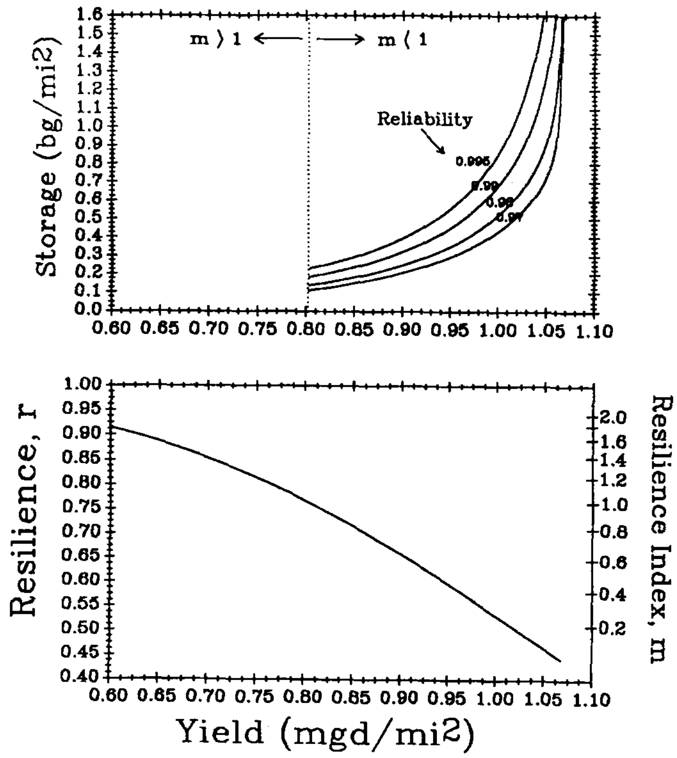

FIG. 7. Regional SRRY Curves for Northeastern United States

are very general because they apply to any surface water supply system in the northeastern United States that exhibits carryover (overyear) storage requirements. We have elected to plot the curves only for yields in excess of about 0.8 mgd/sq mi (1 mgd/sq mi = 1.46 mm/day) because it is only those systems ($m < 1$) that exhibit predominantly carryover or overyear storage requirements. We have reported steady-state reliabilities (1-q) in the range of 0.97–0.995, which is typical of systems that service municipal and industrial water supply users. The values of storage and yield are reported per unit area to make the results understandable and usable to practitioners. Since the regional hydrologic model included basins as small as 1–2 sq mi and basins as large as 6,000–7,000 sq mi (see Fig. 4), Fig. 7 applies to water supply systems in the Northeast with watersheds in that range. Some of the southern regions of the Northeast, such as Long Island, southern Connecticut and southeastern Massachusetts, contain watersheds underlain by very coarse-grained sand aquifers. Surface water impoundments in those regions have significant ground-water contributions that are not described by our relationships, hence Fig. 7 should not be used in those regions.

CASE STUDIES OF WATER SUPPLY SYSTEM BEHAVIOR IN NORTHEASTERN UNITED STATES

To document the usefulness of the results reported in Fig. 7 we applied the regional storage model to four independent systems in the Northeast for which detailed information is available. These four water supply systems, which service New York City, Boston, Springfield, Massachusetts, and Providence, Rhode Island, represent systems with an extremely wide range of drainage areas, reservoir capacities, yields, and overall system behavior, as is summarized in Table 1. The drainage areas, reservoir capacities, and system yields provided in Table 1 were obtained from Scheader (1991), Vogel and Hellstrom (1988), "Safe" (1993), and Deb et al. (1991) for the New York, Boston, Springfield and Providence systems, respectively. In each case, the quoted system yields are obtained from detailed monthly simulation studies that determined the no-failure yield that could be sustained during the worst drought-of-record, which in all four cases was the 1961–1967 drought. These system yields are often referred to as "safe yields" (Deb et al. 1991; "Safe" 1993); however, we prefer the term "historical yield" to emphasize the fact that these yields are simply what could have been delivered if the historical streamflow record were to repeat itself in the future.

Using the reported values of historical system yield, storage capacity, and drainage area, along with the regional hydro-

TABLE 1. Detailed Information Regarding Three Water Supply Systems Used as Case Studies

System (1)	Drainage area[a] (sq mi) (2)	System storage[a] (bG) (3)	Historical system yield[a] (mgd) (4)	Mean annual flow μ (mgd) (5)	Demand α (6)	Resilience Indices m (7)	r (8)
Springfield	48.0	25.4	46	53	0.87	0.53	0.62
Providence	92.8	39.8	90	101	0.89	0.44	0.59
Boston	389.9	265.0	300	315[b]	0.95	0.20	0.51
New York City	1,956.0	547.5	1,290	2,043	0.63	1.48	0.87

Note: 1 sq mi = 2.59 km^2; 1 bG = 3.786 × 10^6 m^3; 1 mgd = 0.0438 m^3/s.

[a]The values of drainage area, system storage, and historical system yield for the Springfield, Providence, Boston, and New York systems are taken from "Safe" (1993), Deb et al. (1991), Vogel and Hellstrom (1988), and Scheader (1991), respectively.

[b]Corrected for required downstream releases.

logic model, allows us to report, in Table 1, the mean annual inflow μ, level of development α, and resilience indices m and r using (3) and (4). The statistics reported in Table 1 are also summarized on SRRY curves in Fig. 8.

If one did not have access to a detailed simulation study for a particular system, and one only knew the storage capacity and drainage area, one could still use Fig. 7 to obtain the relationship between storage, reliability, resilience, and yield. For example, if we had assumed a system reliability of 0.98 for the Boston system, then the yield would have been increased from 1.02 mgd/sq mi (300 mgd or 13.14 m^3/s) to 1.05 mgd/sq mi (308 mgd or 13.49 m^3/s). Since none of the cited studies corresponding to these four cities applied a monthly stochastic streamflow model to estimate the long-term system reliability, one could argue that Figs. 7 and 8 provide more information than any of those detailed at-site simulation studies.

Stochastic streamflow models are now commonly recommended for determining the reliability of water supply systems (Loucks et al. 1981; McMahon and Mein 1986). In fact, Vogel and Stedinger (1988) found that the use of stochastic streamflow models can lead to improvements in the precision associated with estimates of the capacity of water supply systems. Recent research in regional hydrology indicates that regional hydrologic models are often superior to their at-site counterparts. For example, regional regression models of the type developed here, have long been used to predict flood quantiles at ungauged sites, and in a nationwide test regional methods did as well or better than more complex at-site rainfall-runoff modeling procedures (Newton and Herrin 1982). Since the present study uses both a regional hydrologic regression model and a stochastic streamflow model, we expect our results to be comparable to those using at-site hydrology alone.

The four case studies reported here document how our analyses can provide in a few minutes, the type of detailed information about reservoir system behavior that is usually only available after weeks, months, or even years of analyses.

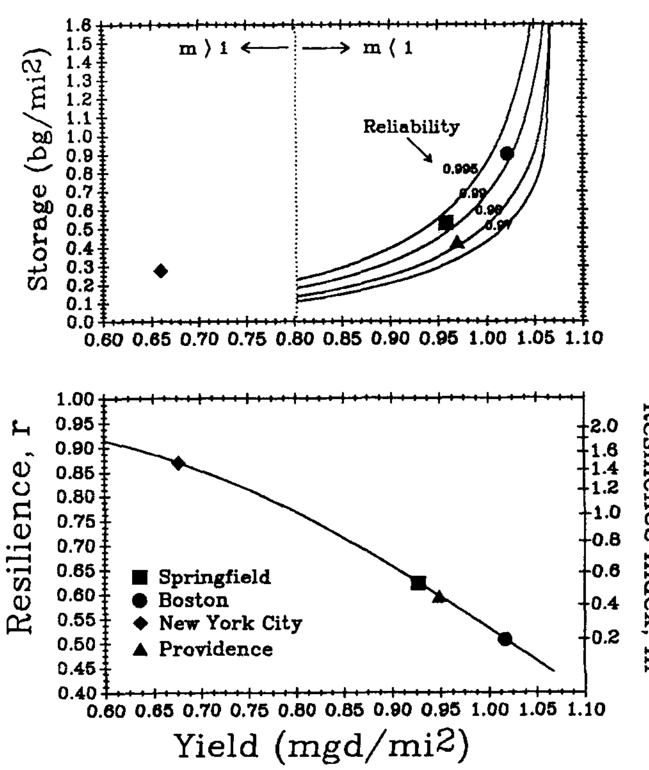

FIG. 8. Regional SRRY Curves for Northeastern United States with New York, Providence, Springfield, and Boston Systems Shown

Detailed comparisons between the behavior of these four systems is provided in the following.

Comparison of Reservoir System Resilience: System Size Is Not Indicative of Its Behavior

Interestingly, even though the New York City (NYC) system has a much larger overall storage capacity and drainage system than the other three systems, it is clearly not dominated by carryover storage, when its yield is only 1,290 mgd (56.5 m^3/s). Therefore, the NYC system, operated at its "historical yield" of 1,290 mgd (56.5 m^3/s) is a much more resilient system than the other three systems because it refills in most years (i.e., $m > 1$). In fact, if a failure occurred, the NYC system would recover with a probability $r = 0.87$, whereas the Springfield, Providence, and Boston systems are much less resilient, with $r = 0.62$, $r = 0.59$, and $r = 0.51$, respectively, due to their large carryover storage requirements. All four systems are very reliable sources, when operated at their historical yield; hence, their resilience or ability to recover from a failure, will not be tested very often.

Evaluation of Impact of Changes in Reservoir Storage and Yield

Fig. 8 documents that the Boston system is on a very steep portion of the storage-yield curve. That is, increases in storage capacity lead to marginal increases in system yield. On the other hand, the NYC system is in a very flat portion of the storage-yield curve, which implies that significant gains in overall system yield can be obtained by increasing overall system storage by building new reservoirs, raising existing dams, or possibly using the existing storage capacity more efficiently.

All four water supply systems are multireservoir systems. For example, the Boston system consists of two reservoirs connected in series, and due to their operating policies, they behave approximately like a single reservoir. In contrast, the NYC system consists of dozens of reservoirs interconnected in both series and parallel. The most our analysis could predict for such a system is the maximum system yield if the entire system of interconnected reservoirs were operated as a single reservoir. However, our analyses cannot even predict that, since the NYC system is not dominated by carryover storage. What our analysis could predict, is how the NYC system would behave, under optimal integrated reservoir operations, if the system yield were increased so that carryover storage dominated system storage requirements. For example, suppose improvements in the operations of the existing NYC reservoir system led to an increased yield of 0.87 mgd/sq mi. This corresponds to a system yield of 0.87 (1956 mi^2) = 1,702 mgd (74.5 m^3/s) $\alpha = 0.83$, $m = 0.67$ and a steady-state system reliability of 0.99. So, even though our analysis does not appear to apply to the NYC system with a yield of 1,290 mgd (56.5 m^3/s), it does apply to the system if the demand (including required downstream releases) is increased to 1,700 mgd (74.5 m^3/s). Interestingly, over the past two decades, the demand on the NYC system has been above it's "historical yield" of 1,290 mgd (56.5 m^3/s), for example, in the 1980s the system yield was in the range of approximately 1,400–1,600 mgd, excluding downstream release requirements. Our analysis provides a rough approximation to the increases in overall system yield that could be obtained by improved and integrated operation of the NYC multireservoir system. Similarly, one could determine from Fig. 8 the gains in system yield beyond 1,700 mgd that could be obtained by adding storage capacity to the NYC system, in addition to improving overall system operations. In all of the examples reported here (except Boston), system demand includes all required downstream releases, so that if downstream release requirements are significant, (in excess of spillage), such as in the case of the NYC system, one must perform further analysis to determine what fraction of the yields in Fig. 8 are due to those downstream release requirements.

Comparison of System Vulnerability

When the consequences of a system failure are severe or catastrophic, the system is said to be vulnerable. Hashimoto et al. (1982) define system vulnerability in terms of the likely magnitude of a failure, if one occurs. One measure of system vulnerability is given by the residence time of water within the system, computed as storage capacity divided by demand. Systems with long residence times tend to take much longer to refill after a failure; hence, they are more vulnerable, because failures are likely to last longer. For example, the Boston system has a residence time of (265 bG·1,000 mg/bG)/(300 mgd·365 d/yr) = 2.4 yr, whereas the residence time is 1.5, 1.2, and 1.2 yr for the Springfield, Providence, and NYC systems. So the Boston system is particularly unique having roughly twice the residence time of the other systems. Fortunately, the Boston system has dropped its demand below its "historical yield" of 300 mgd in recent years due to extensive demand management programs so for that reason, its current reliability is probably greater than any of the other systems. So, even though a failure for the Boston system would last longer and be more severe than for the other systems, failures are less likely to occur for the Boston system.

Comparison with Other Regional Storage-Yield Curves

Fig. 9 compares our generalized SRY curves for the northeastern United States with the storage-yield curves of the "Progress Report of Committee on Rainfall and Yield of Drainage Areas" (1969). Those storage-yield curves were developed using single traces of monthly streamflows for the three river basins shown; hence no reliability estimates are available. The three river basins are the Wachusett and Westfield watersheds in Massachusetts and the Scituate watershed in Rhode Island. Since monthly simulations were used the NEWWA curves are more accurate than our curves for systems dominated by within-year storage requirements. However, our curves are more general because they allow one to evaluate system reliability and system resilience and, more important, our curves are based on a regional hydrologic model of streamflow; hence they contain less sampling variability. It is in part sampling variability that causes the three NEWWA storage-yield curves to differ. Our earlier experiments, summarized in Figs. 2–6, document that most of the apparent differences in the year-to-year hydrologic variability in this region are due to sampling variability and not true differences in hydrology.

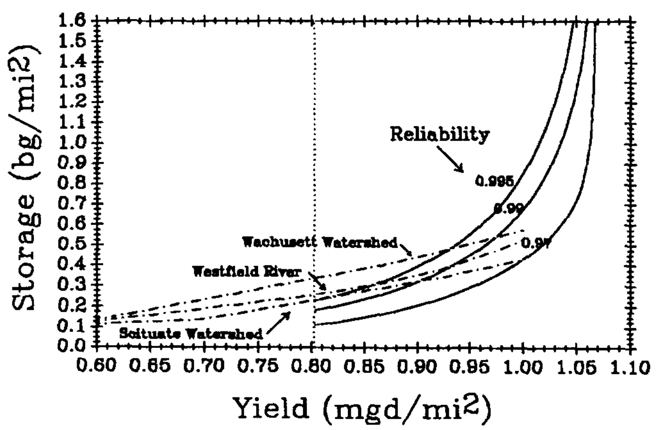

FIG. 9. Comparison of Our Regional RSSY Curves with NEWWA Storage Yield Curves

CONCLUSIONS

The primary objective of the present study was to document that, for a very broad region such as the northeastern United States, recent developments in both regional hydrology and the theory of storage reservoir behavior could be combined to produce general curves describing the relationships among storage, reliability, resilience, and yield. Case studies revealed that the relations reported in Figs. 7 and 8 are very useful for comparing the behavior of very different water supply systems in this region. In some sense, this study is an attempt to organize our thinking about all surface water supply systems and to provide both a language and tool for comparing one system to another.

Usually detailed simulation studies are performed for individual systems and until now, it has been difficult to compare the behavior of existing or proposed water supply systems, without resorting to detailed studies that usually take weeks, months, or years. Using the diagrams reported in Fig. 7, all that is necessary to provide a preliminary evaluation and comparison of the behavior of water supply systems is an estimate of their storage capacities and watershed drainage areas.

Examples of the use of these curves is provided for the water supply systems that service New York, Boston, Springfield, and Providence. Case studies of these systems reveal how each of the individual systems behave and provides a comparison among the systems in terms of their resilience, reliability, and vulnerability to drought events.

Evaluations of time-series of annual average streamflow for 166 basins in the Northeast reveals that this region is remarkably homogeneous in terms of the year-to-year variability and persistence of streamflow. Our evaluations reveal that time-series of annual streamflow in this region are well approximated by a lag-one normally distributed autoregressive process with lag-one correlation coefficient $\rho = 0.19$, coefficient of variation $C_V = 0.25$, and mean annual inflow $\mu = 1.17\, A^{0.985}$ in mgd, where A is drainage area in square miles. These results allowed us to report general relationships among storage per square mile, yield per square mile, reliability and resilience for the entire region, in a single graph. In addition, (2) illustrates how average annual runoff varies, in this region, as a function of average annual temperature and precipitation; hence (2) can be combined with Fig. 7 to evaluate the influence of potential climate change on the behavior of water supply systems in the northeastern United States.

The regional relationships derived in this study are intended for screening-level analysis only and are not intended to replace more complex simulation studies. The relations and methodology introduced here is ideally suited for use in regional and even national level assessments of the vulnerability, reliability, and resilience of water supply systems to future modifications in demand and climate.

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