Storage Reservoir Behavior in the United States

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Abstract: Numerous experiments are performed that characterize the behavior of individual storage reservoirs across the United States. Storage-yield curves based on annual and monthly flow records are compared to show that the standardized net inflow and the coefficient of variation of net inflow C_v completely characterize the refill properties of storage reservoirs. For example, these experiments indicate that for any river with $C_v >$ 0.8, the design capacity of a reservoir is determined by annual fluctuations in streamflow alone, regardless of its size. Two new indices of resilience and vulnerability are derived for reservoirs fed by correlated lognormal inflows. Previous studies document that inflows to reservoirs in the United States may be approximated by correlated lognormal inflows. Combining these results with a recent inventory of thousands of storage reservoirs across the United States, along with regional climate and streamflow databases, we explore the behavior of individual storage reservoirs. We compare the resilience, reliability, yield, and vulnerability of individual storage reservoirs under existing scenarios and one possible future climate scenario.

INTRODUCTION

Most investigations of the behavior of water supply systems focus on an individual system or region. Hundreds of such studies are now available for most developed regions of the world. Few studies have attempted to generalize our understanding of the behavior of individual water supply systems by comparing their behavior. For example, Vogel et al. (1995) compared the behavior of the water supply systems of four cities in the northeastern United States. In the context of previous national water assessments, Select Committee (1960), Lof and Hardison (1966), Wollman and Bonem (1971), and Hardison (1972) examined regional relationships among reservoir storage capacity and yield. The purpose of those studies was to compare the level of streamflow development across the United States and to appraise the amount of water supply that could be made available from utilization of increased levels of surface water storage. Those studies resulted in relationships between storage and yield for broad regions of the United States. Such relations were useful for regional assessments; however those studies did not model or compare the behavior of individual water supply systems as is our primary goal. Another goal of this study is to introduce a methodology for evaluating the behavior of individual reservoir systems that can be used in future regional or national assessments.

Recent developments in computer technology, database management, geographic information systems, and our understanding of storage reservoir behavior enable national assessments of the type performed by Lof and Hardison (1966) and others to be performed using different methods than were used in previous assessments. Previous assessments required aggregation of information on reservoir storage and hydrology in a region to enable simulation of the storage-yield behavior for each region. All reservoirs in a region were added together, along with their drainage areas, and the resulting aggregated systems were modeled, by region. Aggregation of reservoir systems is desirable in regional assessments that seek to estimate the maximum yield that can be obtained from the integrated operation of multiple reservoirs in a region. However, such studies cannot reflect the actual behavior of individual reservoir systems. In reality, some reservoirs in a region are connected and operated conjunctively, whereas others are not. Our approach is to model each individual reservoir system separately. The idea is to evaluate how reservoirs in the United States would behave, if they were each operated independently of one another. The natural extension to this research would be to include information on the exact interconnections between the reservoirs in each region, so that the approach used here could be extended to model those interconnections.

This study attempts to generalize our understanding of the behavior of individual reservoir systems by exploring relationships among climate, hydrology, yield, reliability, resilience, vulnerability, and storage capacity for thousands of individual reservoir systems across the continental United States. To enable such a generalization, considerable simplifications are required. A recently updated computer database known as the National Inventory of Dams (*National* 1996) is used to determine actual reservoir storage volumes across the United States. The hydrologic inflow to each reservoir is computed from regional hydrologic models that relate the mean and variance of annual streamflow to each reservoir watershed area, precipitation, and temperature. Analytical relationships among reservoir system operational characteristics are then used to compare the resilience, reliability, vulnerability, and other performance measures of individual water supply systems, by region, across the continental United States.

STORAGE-RELIABILITY-YIELD RELATIONSHIPS

Vogel et al. (1995) reviewed approaches taken in the development of regional storage-reliability-yield (SRY) relationships. The approaches used by Beard (1963), Lof and Hardison (1966), and Hardison (1972) to develop SRY relations are similar to this study because they are based on fitting a probability distribution to annual streamflows in the region, assuming a fixed value of C_v for the region and deriving an SRY relationship using probability routing methods. Their resulting SRY relations are corrected to include seasonal storage requirements using a method introduced by Beard (1963) and corrected for the serial correlation of annual streamflows using a method described by Hardison (1972).

More recently, analytic SRY relations have been introduced as an alternative to the graphical methods used by Beard (1963), Lof and Hardison (1966), and Hardison (1972). Klemes (1987), Vogel and Stedinger (1987), Buchberger and Maidment (1989), Phien (1993), Vogel and Bolognese (1995), and others reviewed the development of analytic SRY relationships. Simple analytic SRY relationships are not intended to replace more detailed simulation studies; rather, they are

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intended to improve our understanding of the behavior of water supply systems, to allow for comparisons among systems, and for performing regional assessments of water supply. Vogel and Bolognese (1995, Appendix II), Phien (1993), and Vogel and Stedinger (1987) summarized relations among reservoir system storage capacity S, mean annual inflow μ, standard deviation of inflows σ, lag-one serial correlation of the inflows ρ, reservoir yield Y, planning horizon N, and N-year no-failure reliability R_N, in the form

$$S/\sigma = f(\mu, \rho, Y, N, R_N) \tag{1}$$

for systems fed by AR(1) normal, AR(1) gamma, and AR(1) lognormal inflows, respectively. These SRY relationships were developed from Monte Carlo experiments that routed synthetic streamflows through a reservoir using the sequent peak algorithm. Because those relations are complex and reported elsewhere, they are not reproduced here. Pegram (1980), Buchberger and Maidment (1989), and others reported similar relations that are exact results based on the theory of storage.

It is documented in Vogel and Wilson (1996) that annual streamflows in the United States are well approximated by both the lognormal and gamma distributions; therefore either SRY relations developed by Vogel and Stedinger (1987) or Phien (1993) could be applied in the United States. We use the SRY relations for AR(1) lognormal inflows developed by Vogel and Stedinger (1987) because detailed comparisons of the performance of these relations by Vogel and Bolognese (1995) reveal that it compares favorably with exact theoretical results derived by Pegram (1980) and others.

The SRY relationships described above are based on the methodology known as Rippl's mass curve (or its automated equivalent sequent peak algorithm), which assumes that the yield is delivered, without failure, over its planning horizon. A model is also needed that represents the behavior of reservoir systems, once they fail. Vogel and Bolognese (1995) verified that a two-state Markov model is useful and accurate for describing relationships among reservoir system reliability and resilience.

INDICES OF RESERVOIR SYSTEM PERFORMANCE

Water supply system performance measures are receiving considerably increased attention recently as evidenced from a recent nationwide survey on the reliability of existing systems (Harberg 1997). The performance measures of reliability, resilience, and vulnerability have been defined and introduced by a number of previous investigators (Hashimoto et al. 1982). Reliability measures the frequency of failures. Resilience measures the ability of a system to recover from a failure, and vulnerability provides a measure of the magnitude of potential failures. A failure is defined as the inability of a reservoir system to deliver a prespecified yield. In the following sections we outline a conceptual theoretical framework for quantifying these and other performance measures.

Within-Year versus Over-Year Behavior

Actual systems are subject to both within-year and over-year variations in storage; hence, there is no unique division between these two classes of behavior. Within-year systems generally refill each year, whereas over-year systems contain long multiyear drawdown periods and are seldom full. A useful index for classifying the behavior of water supply systems is the index m introduced by Hazen (1914) defined as

$$m = \frac{(1-\alpha)\cdot\mu}{\sigma} = \frac{(1-\alpha)}{C_v} = \frac{\mu - Y}{\sigma} \tag{2}$$

where Y = average annual yield; α = annual yield as a fraction of the mean annual inflow to the reservoir ($\alpha = Y/\mu$); μ and σ = mean and standard deviation of the annual inflows, respectively; and C_v = coefficient of variation of the annual inflows ($C_v = \sigma/\mu$). Vogel and Bolognese (1995) provided a history of the use of the index m in water supply applications. In this study, we term m the standardized net inflow to the reservoir system. Greater values of m correspond to systems that tend to accumulate water in storage over time more than for systems with lower values of m. In this section we document how useful m is, in addition to C_v, for providing a measure of the degree to which the design capacity of a reservoir system depends on within-year (seasonal) versus over-year (carryover) storage requirements.

Storage-yield curves are computed using historic annual and monthly streamflow traces for the 10 streamflow gauges summarized in Table 1. These sites were selected to reflect the range of interannual variability of streamflow across the entire United States with values of C_v that range from 0.23 to 0.85. Table 1 summarizes the name, location, record length, drainage area, lag-one serial correlation of the annual flows $\hat{\rho}_1$, annual average rainfall, runoff ratio, and C_v of the annual streamflows for these 10 sites. Fig. 1 compares the storage-yield curves for the 10 watersheds based on monthly and annual streamflow series. Storage-yield curves were computed using the sequent peak algorithm that is equivalent to the use of a storage-mass curve. This algorithm estimates the minimum reservoir capacity required to deliver the specified yield, without failure, over the historic period. On the abscissa in Fig. 1, we plot both the level of development α ($\alpha = Y/\mu$) and the standardized net inflow m, defined in (2). Both m and α are surrogates for system yield, because as yield Y increases, α increases and m decreases; however, because both indices are standardized, they can be generalized across systems. Fig. 1 reflects storage-yield curves that correspond to nearly all possible reservoir systems at each of the 10 sites. Along the ordinate of Fig. 1, we plot the storage ratio S/μ.

TABLE 1. Hydrologic Information for 10 Streamflow Gauges Used to Construct Storage Yield Curves in Fig. 1

USGS gauge number (1)	Site name (2)	State (3)	Length of record (water years) (4)	$\hat{\rho}_1$ (5)	Drainage area (km^2) (6)	Annual rainfall (cm) (7)	Runoff/Rainfall (cm/cm) (8)	C_v (9)
01144000	White River at West Hartford	Vermont	60	0.26	1,787	105	0.55	0.23
12027500	Chehalis River near Grand Mound	Washington	59	0.03	2,318	160	0.67	0.25
09239500	Yampa River at Steamboat Springs	Colorado	77	0.15	1,564	64	0.42	0.28
07375500	Tangipoha River at Robert	Louisiana	50	0.21	1,673	152	0.40	0.34
07072000	Elevenpoint River near Ravenden Springs	Arkansas	53	0.30	2,937	109	0.31	0.41
06933500	Gasconade River at Gerome	Missouri	65	0.33	7,356	107	0.29	0.48
06810000	Nishnabotna River above Hamburg	Iowa	60	0.32	7,268	76	0.18	0.65
10322500	Humboldt River at Palisade	Nevada	75	0.34	12,976	23	0.12	0.75
11152000	Arroyo Seco River near Soledad	California	87	0.03	632	86	0.28	0.81
08146000	San Saba River at San Saba	Texas	73	0.10	7,889	66	0.04	0.85

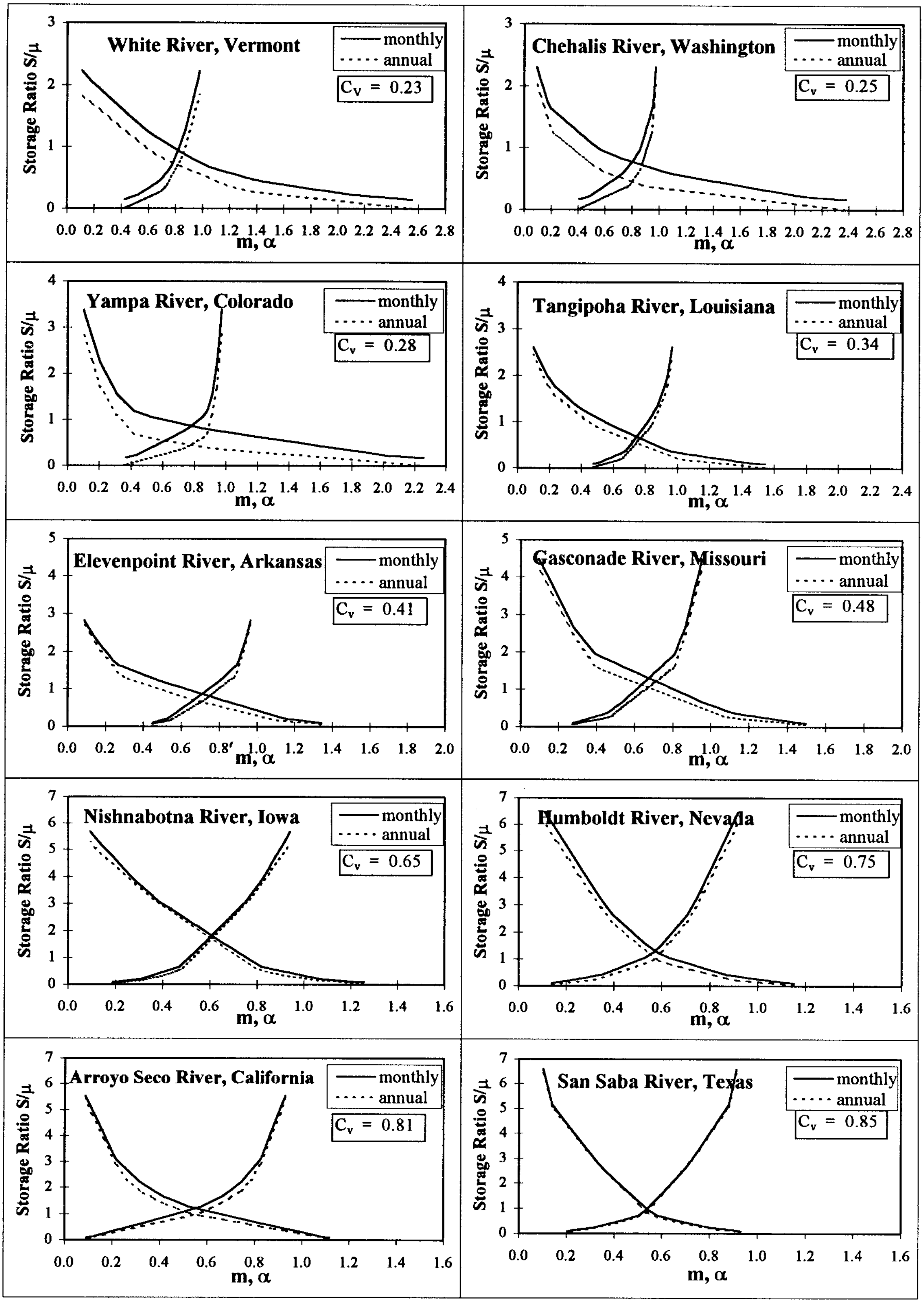

FIG. 1. Storage-Yield Curves Based on Monthly and Annual Flow Records

The storage-yield curves based on monthly flows are always above the storage-yield curves based on annual flows because monthly curves include seasonal and carryover storage requirements. For sites with high streamflow variability ($C_v > 0.3$), storage-yield curves based on annual flows provide a good approximation to storage-yield curves based on monthly flows, and that approximation improves as C_v increases. We found that for $m < 1$, the percentage difference between storage ratios based on monthly and annual flow series is usually less than about 30% with the difference dropping to zero for $C_v > 0.8$. [See Ravindiran (1997) for further details.] Previous investigators have hypothesized that $m = 1$ can be considered as a demarcation between over-year and within-year systems because carryover storage requirements increase significantly as m decreases below unity. Fig. 1 illustrates that knowledge of both C_v and m is required to understand the relationship between seasonal and carryover storage requirements. The use of an annual time step provides a reasonable approximation (to within 30%) to monthly storage-yield curves as long as the standardized net inflow m is less than unity and $C_v > 0.3$, with that approximation improving as C_v increases. This result supports the recommendations of previous studies (Vogel and Stedinger 1987; Vogel and Bolognese 1995) but to our knowledge is the first time this hypothesis has been verified using actual streamflow data.

Carryover storage results from either a large C_v or high yield Y (hence high α), or both. Interestingly, Fig. 1 documents that the necessary reservoir capacity in a region with C_v greater than about 0.8 will be determined by carryover storage requirements, regardless of the yield of the system! Similarly, the necessary reservoir capacity of systems with $m > 1$ and/or $C_v < 0.3$ will be determined by seasonal storage requirements.

Factors other than m and C_v could influence the degree to which carryover storage dominates system behavior. For example, if one were to modify system operations to allow for lower reliability than the sequent peak algorithm allows, additional failures would be possible making within-year operations more important. Therefore, reliability can also influence the degree to which a system exhibits carryover storage requirements.

Reservoir System Resilience

Hashimoto et al. (1982) defined resilience as the probability of recovery from a failure once a failure has occurred. That definition is used here, with failure defined as the inability of the reservoir system to provide its target yield Y in a given year. Vogel and Bolognese (1995) used a two-state Markov model of reservoir system states to show that resilience r may be estimated using

$$r = \Phi\left[\frac{1}{\sqrt{1-\rho^2}}\left(m - \frac{\rho}{\Phi(-m)\cdot\exp\left(\frac{m^2}{2}\right)\cdot\sqrt{2\pi}}\right)\right] \quad (3)$$

for a reservoir fed by AR(1) normal inflows, where $\Phi(\text{arg})$ denotes the cumulative normal density function applied at arg; m is given in (2); and ρ is equal to the lag-one correlation of the inflows. The index r is the probability that the reservoir system will provide the stated yield Y, in a year following a failure. The resilience depends upon the statistics of the inflow and yield, rather than on the size of the reservoir system. Using (13) in Vogel and Bolognese (1995) and a derivation analogous to that which led to (3), we derive here the resilience of a reservoir system fed by AR(1) lognormal inflows resulting in

$$r = \Phi\left[\frac{1}{\sqrt{1-\rho_y^2}}\left(-B - \frac{\rho_y}{\Phi(B)\cdot\exp\left(\frac{B^2}{2}\right)\cdot\sqrt{2\pi}}\right)\right] \quad (4)$$

where $B = [\ln(\alpha\mu) - \mu_y]/\sigma_y$; $\mu_y = \ln[\mu/\sqrt{1 + C_v^2}]$; $\sigma_y^2 = \ln[1 + C_v^2]$; and $\rho_y = \ln[1 + \rho(\exp(\sigma_y^2) - 1)]/\sigma_y^2$. Here μ, σ, and ρ are the mean, standard deviation, and lag-one correlation of the inflows, respectively; and μ_y, σ_y, and ρ_y are the mean, standard deviation, and lag-one correlation of the natural logarithms of the inflows, respectively. The resilience of a reservoir system tends to increase as m increases or as ρ decreases, or both.

Reservoir System Reliability

Stedinger et al. (1983, Appendix) and Vogel and Bolognese (1995, equation 17) used a two-state Markov model to relate the N-year no-failure reliability R_N to the steady-state annual reliability R_a. Their relation can be rearranged to yield

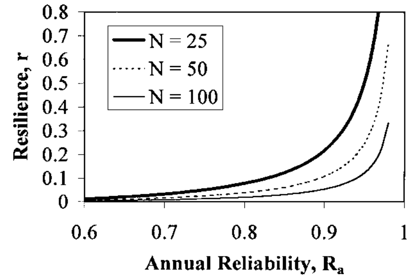

FIG. 2. Relationship between Resilience *r* and Annual Reliability R_a Corresponding to *N*-Year Failure Free Reliability R_N = 0.5

$$r = R_a\left[\frac{1 - \left(\frac{R_N}{R_a}\right)^{1/(N-1)}}{1 - R_a}\right] \quad (5)$$

where r = resilience defined in (3) and (4) for systems fed by AR(1) normal and lognormal inflows, respectively; and N = length of the planning period. No-failure reliability R_N is the probability that a reservoir will provide a constant yield Y, without failure, over an N-year period. Annual reliability R_a is the steady-state probability, in a given year, that the reservoir system will deliver the stated yield. Therefore, the reservoir system fails to deliver its yield $(1 - R_a)$% of the time. Fig. 2 illustrates the relationship between resilience r and annual reliability R_a for an N-year failure free reliability of $R_N = 0.5$ and planning periods of N = 25, 50 and 100 years. Note that, in general, systems with high annual reliability also exhibit high resilience.

Reservoir System Vulnerability

Reservoir system vulnerability provides a measure of the magnitude of a failure, should it occur. Although most water supply systems are designed with a very small probability of failure, attention should be paid to the nature of such failures, particularly when the cause of such failures is itself subject to tremendous uncertainty (i.e., climate change). Hashimoto et al. (1982) suggested one metric of system vulnerability as the expected maximum severity of a failure. Beard (1963) introduced a shortage index that he defined as the sum of squares of the annual shortages. We employ the definition introduced by the ASCE Task Committee on Sustainability Criteria (ASCE 1998) who defined vulnerability as the conditional expected volume of a failure. We compute it as the conditional mean deficit using a long simulation experiment. The conditional mean deficit is computed using only the years in which failures occur.

Reliability provides a measure of how often a system fails. Resilience provides a measure of how long failures will last, and vulnerability provides a measure of how severe failures may become. What is needed is a simple vulnerability index, analogous to the resilience index r, the reliability index R_a, and the standardized net inflow index m (described above). Because no such indices are currently available, Monte Carlo experiments are performed to develop and test some simple vulnerability indices.

Vulnerability Experiments

In this section, failures are simulated for a wide class of reservoir systems to evaluate various vulnerability indices. Assume a reservoir of capacity S is designed to deliver a yield Y, without failure, over an N = 50 year planning period. This is equivalent to the approach used in the design of most water supply reservoirs in current use in the United States. They were designed by applying the sequent peak algorithm (or equivalent mass curve) over the available period of streamflow record. Over many such (independent) designs, one expects the N-year no-failure reliability to be $R_N = 0.5$. That is, there is a 50% chance that future N-year periods will be either wetter or drier than the historical one. This assumption is reasonable if all reservoirs in a region are assumed to act independently of each other. Unfortunately, this is not the case for many reservoirs but is assumed here due to the lack of better information. Each reservoir is assumed to be fed by a watershed with mean annual inflow μ, standard deviation of annual inflows σ, and lag-one correlation ρ, with annual streamflows following an AR(1) lognormal model. Each combination of μ, σ, and level of development $\alpha = Y/\mu$ leads to a value of m. The required reservoir design capacity S corresponding to the specified values of m, ρ, $N = 50$, and $R_N = 0.5$ is obtained for AR(1) lognormal inflows from analytic expressions given by Vogel and Stedinger (1987).

Assuming the reservoir starts full, the reservoir contents are simulated over a 50,000 year period. Whenever the reservoir contents plus inflow are insufficient to satisfy the yield Y, a failure is noted. The average value of all such failures, as a fraction of the required yield Y, is termed the average deficit as a fraction of yield and is denoted D. Our goal was to find a simple index or combination of system parameters μ, σ, ρ, α, Y, S, and m that is always related to D in the same fashion, regardless of the size of the reservoir, yield, or the hydrologic conditions on that system. After many trials, we found that storage capacity S was consistently correlated with the magnitude of the average deficit. The storage yield ratio S/Y was also correlated with the magnitude of the average deficit denoted as a fraction of system yield D as is illustrated in Fig. 3. The relationship illustrated in Fig. 3 is similar if one plots S versus the product DY, instead of S/Y versus D; hence spurious correlation is not an issue here. Fig. 3 results from 40 Monte Carlo experiments with values of m ranging from 0.1 to 1.0, values of C_v ranging from 0.3 to 0.8, and values of ρ ranging from 0 to 0.5. The relationship between S/Y and D remains approximately the same, regardless of the hydrology, yield, or reservoir capacity. We conclude that S/Y is a useful metric for comparing the vulnerability of different reservoir systems. One can estimate D directly from S/Y using the regression equation

$$D = 0.452 \left[\frac{S}{Y}\right]^{1.27} \tag{6}$$

which is illustrated in Fig. 3. Eq. (6) has an adjusted $R^2 = 0.936$ (in log space), normally distributed residuals, and model coefficients with t-ratio's in excess of 20.

The ratio S/Y represents the number of consecutive years of water supply yield in storage, when the system is full. Many other vulnerability indices were tested, such as S/μ, S/m, $S/(\mu - Y)$, and others; however, none were invariant to hydrology, yield, and storage capacity, as was S/Y.

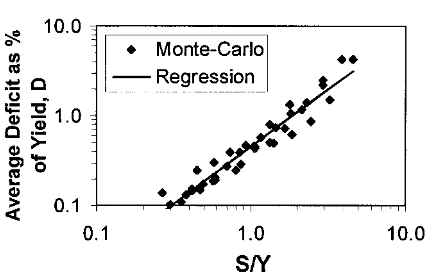

FIG. 3. Relationship between Vulnerability Index *D* and Storage/Yield Ratio *S/Y* for Wide Class of Hydrologic Inflow and Yield Scenarios

BEHAVIOR OF STORAGE RESERVOIRS IN THE UNITED STATES

In the following sections, experiments are performed that explore the behavior of actual reservoirs across the continental United States using the indices introduced above. Using a national database of reservoir information, in combination with (1)–(6), and regional hydrologic models of the mean μ and variance σ^2 of streamflow, we determine the distribution of reservoir reliability, resilience, vulnerability, and level of development, by water resource region. Reservoir behavior is examined using the historical climate and a hypothetical future climate scenario based on a general circulation model (GCM). We begin by describing the regional hydrologic model used as input to each reservoir system, followed by a description of the reservoirs considered, climate input assumptions, and finally by the results of the reservoir simulations.

Regional Hydrologic Model

A flexible hydrologic model is required to estimate the mean and variance of annual inflows to each reservoir in the United States under existing and future climate conditions. The model must depend on the watershed area feeding each reservoir and its associated climate. The regional hydroclimatologic regression equations developed by Vogel et al. (1999) for the continental United States were used. The regional equations for the mean μ and variance σ^2 of annual streamflow are

$$\mu = aA^bP^cT^d; \quad \sigma^2 = eA^fP^gT^h \tag{7a,b}$$

where the letters a–h are model parameters; A = drainage area; P = mean annual precipitation; and T = mean annual temperature. Eq. (7) is used along with estimates of A, P, and T for each of the reservoir sites to compute the mean and variance of the annual inflows to each reservoir.

Vogel et al. (1999) developed a separate set of regional regression equations [(7a) and (7b)] for each of the 18 water resource regions depicted in Fig. 4 using historical hydrologic characteristics μ and σ^2, and basin characteristics A, P, and T estimated from 1,556 basins. The resulting regional regression equations have (log space) R^2 values for (7a) ranging from 80 to 99.7% with an average value of 94.6%. All regions, except 10, 12, and 15, had (log space) R^2 values in excess of 90%. [See Vogel et al. (1999) for a more detailed discussion of these regional models.]

Reservoir Database

We employ the national inventory of 75,187 dams developed by the Federal Emergency Management Agency (*Na-*

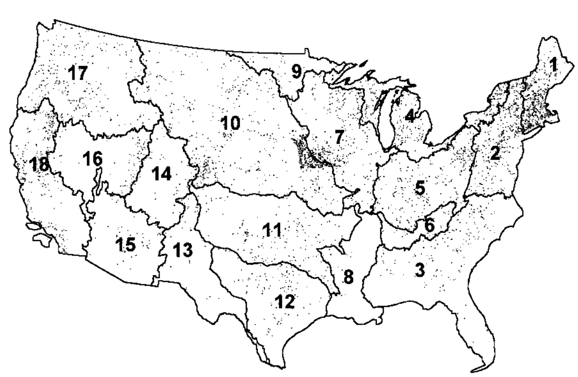

FIG. 4. Location of Reservoirs Used in this Study Along with Boundaries of 18 Water Resource Regions

tional 1996) and the U.S. Army Corps of Engineers. This inventory is a computer database created to track information on the nation's water control infrastructure. The information used in this study includes drainage area *A*, reservoir storage volume *S*, use and location of dam. Excluding dams outside the continental United States leaves 74,914 dams. Excluding reservoirs without information regarding their purpose leaves 55,247 dams. Because geographic information system methods are used to estimate climate and hydrologic inputs to each reservoir, dams without latitude and longitude information and storage volume information were dropped. Data quality assurance procedures were also used to eliminate erroneous data. Because the database is for dams, and it is possible for a single reservoir to contain several dams, duplicate dams were removed, leaving 51,749 dams that met all of the above criteria.

Because the purpose of this study is to investigate the behavior of storage reservoirs whose function is to store and release (or regulate) water supply, only reservoirs whose purpose involves flow regulation are included, leaving only 23,316 dams. Reservoirs that regulate flow for water supply are interpreted as reservoirs whose purpose involves one or more of the following functions: irrigation, hydroelectricity, navigation, water supply, or fire protection. To avoid any extrapolation in the use of the regression equations [(7*a*) and (7*b*)], dams with drainage areas either larger than the maximum or smaller than the minimum drainage basin used to estimate the regional regression equations were removed leaving 5,392 dams. Fig. 4 illustrates the location of the remaining 5,392 reservoirs used in this study, along with the boundaries of the 18 water resource regions introduced by the U.S. Water Resources Council in 1970 for the purpose of assessing the state of water resources across the nation (U.S. 1975). Fig. 5 compares the total reservoir capacity, by region, with the total reservoir capacity of the smaller database of reservoirs (5,392) used in this study. Fig. 5 documents that even though we are modeling a small fraction of the reservoirs in the country, those reservoirs make up a significant fraction of the entire storage capacity in most regions of the United States.

Climatic Inputs

The current climate is assumed to equal the historical climate. The possible future climate scenario corresponds to a doubling of greenhouse gases above current levels, based on the GISS (Goddard Institute for Space Studies) transient atmosphere-ocean coupled GCM (Russell et al. 1995). The temperature increases are generally in the range of 1.7 to 2.4°C. In this GISS GCM scenario, annual average precipitation generally increases across the continent; however, decreases occur in portions of the southwest, upper midwest, and southeastern regions of the United States. Precipitation estimates produced by GCM scenarios are known to be uncertain. Consider this particular GCM scenario as simply one possible future scenario among many possible scenarios.

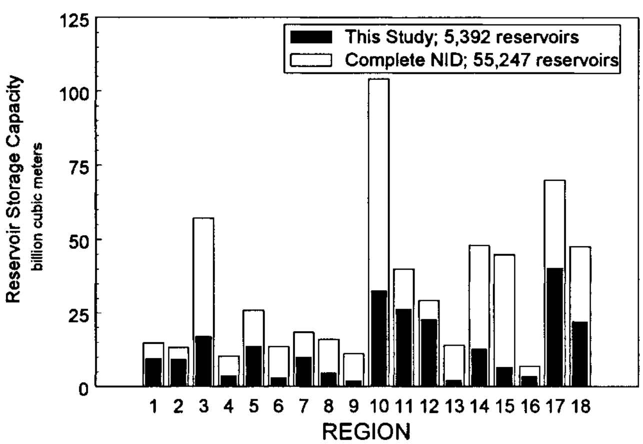

FIG. 5. Comparison of Storage Capacity of All 55,247 Reservoirs with 5,392 Reservoirs Used in this Study

Hydrologic Impacts

Estimates of average annual temperature *T* and average annual precipitation *P* were obtained for each reservoir depicted in Fig. 4 using PRISM climate grids [see Vogel et al. 1999]. We assume that the climate surrounding each reservoir reflects its watershed because it was infeasible for us to delineate the drainage basins corresponding to the thousands of reservoirs modeled in this study. Future values of *T* were obtained for each reservoir site by adding the temperature increases predicted by the GISS GCM to the historical values of *T* from the PRISM grids. Future values of *P* were obtained for each reservoir site by multiplying the historical values of *P* by the changes in *P* predicted by the GISS GCM. The values of *P* and *T* corresponding to both current and future climate conditions were then introduced into (7), resulting in estimates of climate change impacts on μ and σ. It is documented in Lane (1997) that the spatial variations in the values of *P* and *T* used to fit the regional regression models in (7) were approximately the same as the variations in *P* and *T* that result from this GISS GCM scenario. In other words, little or no extrapolation of (7) was required when modeling the hydrologic impacts of the GISS GCM scenario. This is unique, because when physically based watershed models are used in climate change investigations, extrapolation is always required. Still, it is possible that climate change will produce changes in the structure of the regional hydrologic relationships, so that these relationships may not reflect future hydrologic conditions in a changed climate.

Vogel et al. (1997) compared the use of regional regression models similar to (7), with more detailed physically based daily streamflow models for determining the impact of climate change on annual streamflow for four catchments in New York and one in Massachusetts. It was documented in Vogel et al. that regional regressions such as (7) can provide excellent agreement when compared with more detailed hydrologic models in investigations of the hydrologic impacts of climate change. Unfortunately, the use of regional hydrologic regression procedures in climate change investigations has only been validated in the temperate northeast where such regression models perform best.

Fig. 6 uses boxplots to illustrate the variation in estimates of the mean and coefficient of variation C_v, of average annual inflows to the reservoirs by region, under the historical climate and a future GISS climate. Fig. 6 illustrates that the mean annual inflow will decrease in most regions of the United States under a GISS climate, whereas the coefficient of variation will generally increase. The decrease in the mean annual inflow results from the increases in temperature predicted by the GISS GCM. As expected, C_v is much higher in the western regions of the United States than the eastern regions. These results indicate generally less water availability and generally increased overall hydrologic variability under this particular future GISS climate.

Storage Reservoir Simulation Results

This section applies the reservoir performance indices to each of the 5,392 storage reservoirs illustrated in Fig. 4. Our assumption is that each reservoir was designed using the sequent peak algorithm (also known as Rippl's mass curve) with a 50-year historical streamflow record. This implies that the no-failure *N*-year reliability R_N = 0.5 and 50 years, in (1), (5), and (6). This should mimic the way most reservoirs in the

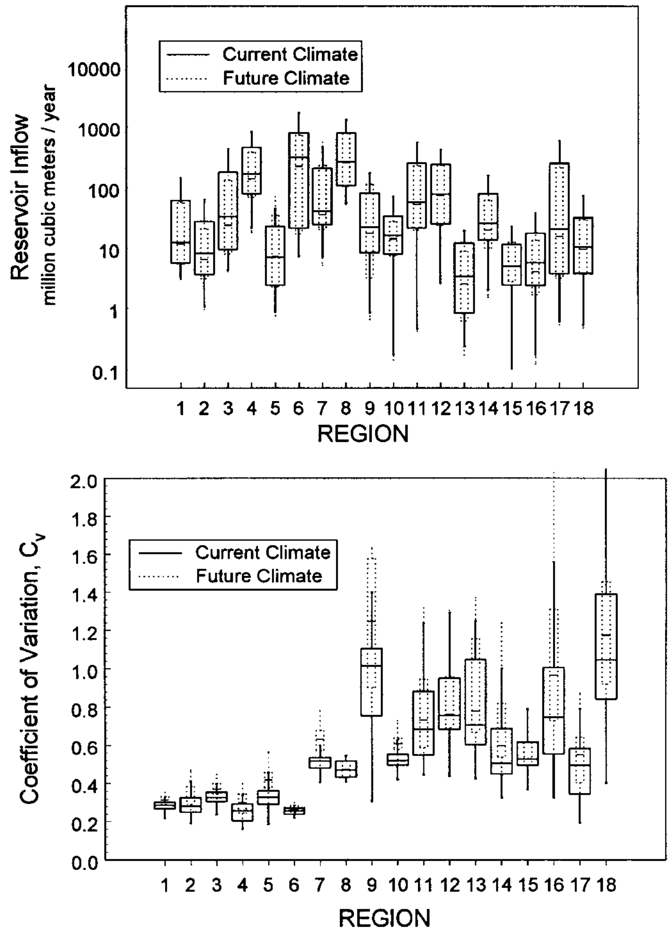

FIG. 6. Boxplots of Variation in Mean Reservoir Inflow and Coefficient of Variation C_v of Average Annual Inflows to Reservoirs within Each Region under Existing Climate and Future GISS Climate

United States were designed because the sequent peak algorithm (or its automated equivalent Rippl's mass curve) is (was) the standard design method in the United States, and this algorithm assumes no-failure operations over the N-year period used in the simulation.

The inputs to the reservoir simulations include the mean μ and variance σ^2 of annual streamflow, planning horizon N = 50, N-year no-failure reliability R_N = 0.5, reservoir storage capacity S, and lag-one serial correlation of the annual inflows ρ. The values of μ and σ are obtained from the regressions in (7) that require the following as input: drainage area A, precipitation P, and temperature T, corresponding to each reservoir site. Estimates of ρ for each reservoir are obtained using the unbiased regional estimators developed by Vogel et al. (1998). These values of μ, σ, ρ, N, R_N, and S are substituted into (1) leading to an estimate of reservoir yield Y. This information is then used to compute the following reservoir performance indices.

Within-Year versus Over-Year Operations

The estimates of μ, σ, and Y are used in (2) to obtain the standardized net inflow m and the level of development $\alpha = Y/\mu$ of each reservoir. Fig. 7 illustrates the relationship between m and C_v for the reservoirs in Regions 1 and 18. Also shown using a solid curve (hyperbola) is the relationship $m = (1 - \alpha)/C_v$ when $\alpha = 0$. The space between the solid hyperbola representing $\alpha = 0$ and the x-axis represents the feasible space for all reservoirs, because the x-axis represents a standardized net inflow of $m = 0$ or $\alpha = 1$. Fig. 7 shows that as C_v increases above unity, m is always less than unity, so that the capacity of reservoir systems with $C_v > 1$ must be determined primarily by carryover water storage requirements. Fig. 7 also shows the distribution of individual reservoir systems in Regions 1 and 18. Also shown on Fig. 7 is a dashed line with a slope of unity, which we found provides a good overall demarcation between systems dominated by within-year versus over-year behavior.

Fig. 8 illustrates boxplots of m and α for each of the reservoirs, by region, under existing and the GISS GCM scenario. As expected, most of the reservoirs in the temperate east (Regions 1–6) exhibit $m > 1$, whereas reservoirs in the semiarid west (Regions 13–18) exhibit $m < 1$. Recall that reservoir operations are mostly within-year when C_v is less than about 0.3 and $m > 1$, which is the case in the eastern regions. Similarly, reservoir operations are mostly over-year when C_v is

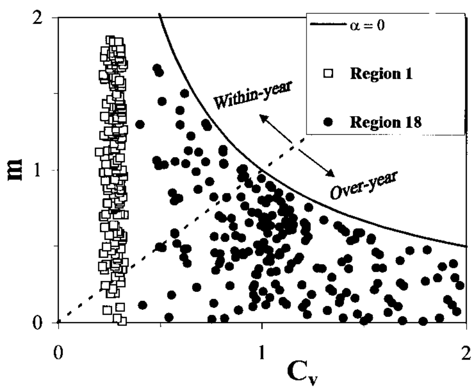

FIG. 7. Plot of Standardized Net Inflow m versus Coefficient of Variation of Inflows C_v for Regions 1 and 18

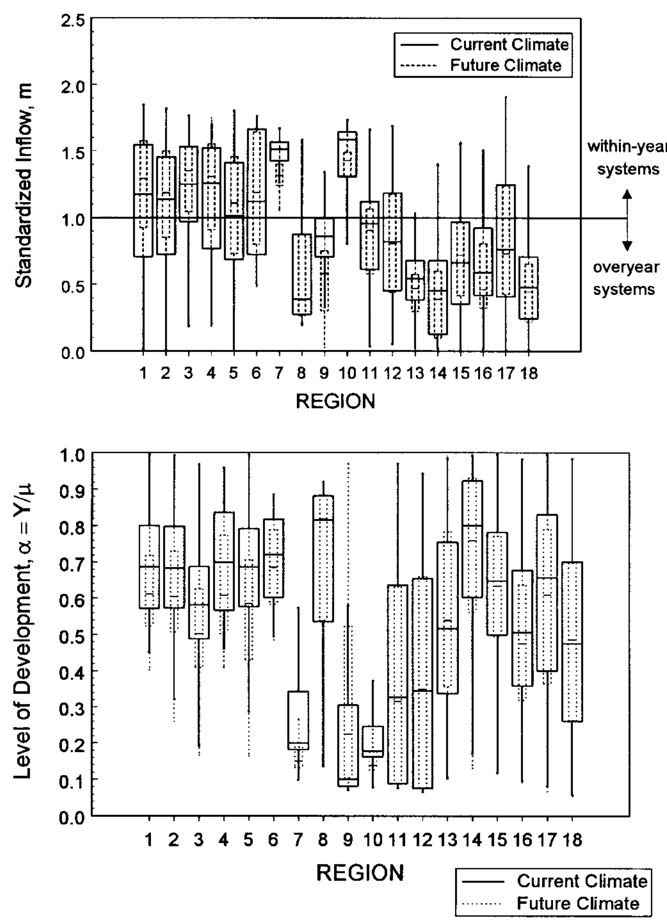

FIG. 8. Boxplots of Standardized Net Inflow m and Level of Development $\alpha = Y/\mu$ of Reservoirs within Each Region under Existing Climate and Future GISS Climate

larger than about 0.6–0.8 and $m < 1$ as is the case for the western regions. Within-year operations can result from either low C_v, low level of development $\alpha = Y/\mu$, or both. Fig. 8 shows that levels of development are nearly always greater than about 50% of the mean annual flow in the eastern regions. In spite of the uniformly high levels of development associated with reservoirs in the east, their reservoir capacity is still determined by within-year operations. This is due to the very low values of C_v in eastern regions, reported earlier in Fig. 8.

Interestingly, the necessary capacity of nearly all reservoirs in the country, west of the Mississippi River (Regions 8, 9, and 11–18) are determined by over-year storage behavior, with the exception of most reservoirs in the upper Missouri Region 10 and a few reservoirs in Regions 11, 12, and 17. In some instances, over-year behavior results from very high levels of development and relatively low values of C_v as is the case in Regions 8 and 17. In other instances, over-year behavior results from relatively low levels of development but high values of C_v such as in Region 9. More often, over-year behavior results from a combination of both high values of C_v and α as is the case in the semiarid southwestern Regions 13–16 and 18.

Level of Development

Fig. 8 demonstrates that the impact of this particular climate change scenario is to increase the level of development in the west and decrease it in the east. Fig. 6 shows that mean inflows will be lower for all regions of the United States under this future GISS climate; hence reservoir yield will also generally be lower for all regions, in a future GISS climate. Nevertheless, reservoir yields will drop less than inflows for the within-year systems of the east, and Fig. 8 illustrates that levels of development will actually be lower under a future climate, than under the current climate, in eastern regions. Therefore, systems in the east will behave more within-year, and systems in the west will behave more over-year, under future climate conditions than they do now. This unexpected effect was confirmed from an examination of individual storage-yield curves.

Storage Ratio

Perhaps the simplest and most common overall index of reservoir performance is the storage ratio S/μ summarized, using boxplots in Fig. 9. Reservoirs in the more temperate eastern regions generally store <1 year of water, whereas it is not uncommon for reservoirs in the west to store several years of water. Because the impact of climate change is to generally decrease the mean inflows, the storage ratios generally increase under this particular GISS climate. Many of the reservoirs in the west have storage ratios less than unity, even though those reservoirs are governed by over-year reservoir behavior. A comparison of Figs. 8 and 9 reveals that if a reservoir has a storage ratio in excess of unity its design capacity is determined by over-year operations; however, if the storage ratio is less than unity, the reservoir capacity is not necessarily determined by over-year operations. The storage ratio, although commonly used to characterize overall reservoir operations, is not nearly as informative as other indices introduced here.

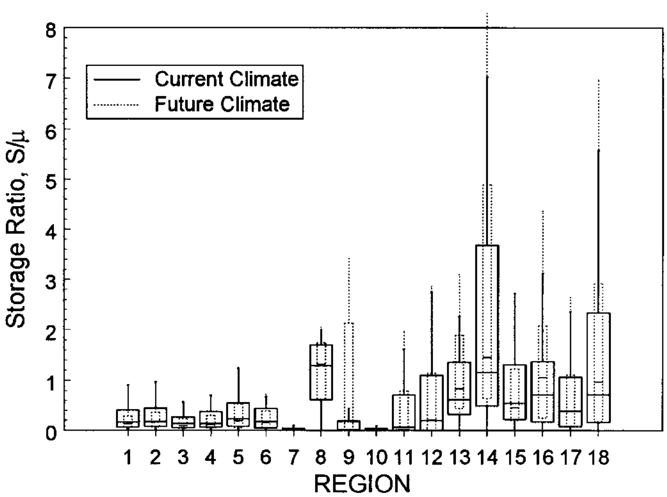

FIG. 9. Boxplots of Reservoir Storage Ratios under Existing Climate and Future GISS Climate

Reservoir Resilience, Reliability, and Vulnerability

Fig. 10 illustrates the distribution of resilience r, annual reliability R_a, and vulnerability D, computed using (4), (5), and (6), respectively. The resilience r, reflects the probability that

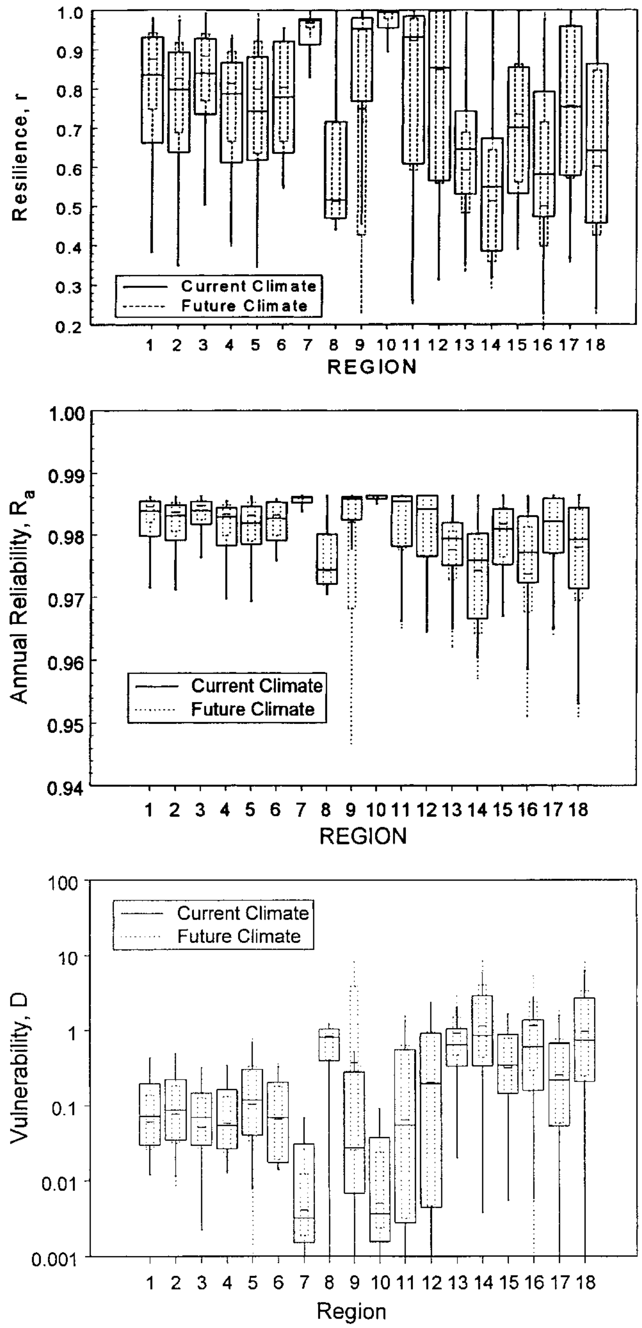

FIG. 10. Boxplots of Reservoir Resilience, Reliability, and Vulnerability under Existing Climate and Future GISS Climate

the reservoir will deliver its stated yield in a year following a failure. Reservoirs characterized by within-year operations tend to have much higher resilience than over-year systems because they refill quickly. Under this GISS climate scenario, reservoirs in the east become more resilient whereas reservoirs in the west become less resilient. This result is due to decreases in the level of development that result for reservoirs in temperate climates as was illustrated in Fig. 8.

Annual reliability reflects the steady-state probability that a reservoir will deliver its yield, without failure, in a given year. Generally, the annual reliability of reservoirs across the United States is nearly constant in the range of 0.97–0.985. Regions 8 and 14, which exhibited the lowest standardized net inflows in Fig. 8, also exhibit the lowest reliabilities in Fig. 10. Under the future GISS climate, reservoir systems in the east experience slight increases in reliability, and systems in the west experience slight decreases.

Vulnerability D reflects the average number of consecutive years the system could potentially fail to deliver its yield. A vulnerability of unity ($D = 1$) implies that on average, a reservoir system failure is equivalent to 1 year of system yield. As expected, the more resilient systems in the east will nearly always have failures that last <1 year. Systems in the western regions are generally much more vulnerable with typical failures lasting many years. Naturally, systems respond to drought with conservation and reallocations, so that real reservoir systems are not nearly as vulnerable as indicated in Fig. 10, during drought. Nevertheless, Fig. 10 reflects the magnitude of potential water supply failures if no conservation or reallocation mechanisms were available.

CONCLUSIONS

This study has sought to document the overall behavior of storage reservoirs in the United States under existing scenarios and one of many possible future climate scenarios. We began by introducing numerous indices of reservoir system performance, including measures of system resilience, reliability, and vulnerability. The study then applied these indices to thousands of individual storage reservoirs across the United States under existing scenarios and one future climate scenario.

We document the conditions under which reservoirs exhibit within-year and over-year behavior. It was shown that the coefficient of variation of annual inflows C_v and the standardized net inflow m, together, can be used to determine whether reservoirs tend to refill at the end of each year (within-year) or whether they are seldom full at the end of a year (over-year). We also summarized numerous other indices of reservoir system performance including measures of system reliability and resilience that have been introduced previously. Monte Carlo experiments document that reservoir system vulnerability, or the magnitude of system failures, can be predicted using the ratio of storage capacity to yield S/Y. An equation was developed that relates reservoir system vulnerability to the ratio S/Y.

The indices of reservoir system performance were combined with a regional hydroclimatologic model of annual streamflow introduced by Vogel et al. (1999) and an inventory of storage reservoirs for the United States. The results led to the following general conclusions regarding the behavior of individual storage reservoirs in the United States:

1. A general classification system was introduced in Fig. 7 for determining whether reservoir capacity is determined by within-year or over-year behavior. The approximate classification scheme illustrated in Fig. 7 classifies within-year systems as systems with $C_v < 1$ and standardized inflow in the range $C_v \leq m \leq (1/C_v)$. Similarly, over-year systems are classified as either systems with $C_v > 1$ or systems with $C_v < 1$ and standardized inflow in the range $0 \leq m \leq C_v$. This classification scheme is consistent with all of the results of this study, including those documented in Figs. 1, 7, and 8.
2. Our approach is simplistic because it treats reservoirs as if annual variations in climate and hydrology are all that matter. The use of an annual model of reservoir operations has enabled us to examine the general behavior of thousands of individual reservoirs. This approach is useful in regional climate change assessments, which seek to identify regions of vulnerability and for national and regional water assessments. Since we ignore the interconnections among reservoirs and their coordinated operations, our results only approximate the behavior of individual reservoirs operated independently. Previous national storage-yield assessments by Select Committee (1960), Lof and Hardison (1966), Wolman and Bonem (1971), and Hardison (1972) aggregated storage over the 18 regions depicted in Fig. 4. Hence, those studies assumed all storage reservoirs in a region are operated conjunctively, which is also not realistic. Future research should attempt to integrate information on the interconnections among reservoir systems.
3. Generally, the necessary capacity of reservoir systems in the east is determined by within-year water storage requirements, and systems in the west are determined by over-year water storage requirements. Over-year systems tend to have much lower resilience and slightly lower reliability than within-year systems. Over-year systems tend to be much more vulnerable systems than within-year systems, and this effect is particularly pronounced under conditions of modest climate change.
4. Reservoir system reliability and resilience are positively correlated.
5. We can generally expect less water availability and increased overall hydrologic variability under the future GISS climate scenario used here. The impacts of these changes in climate will differ for within-year and over-year reservoir systems. Although overall system yields will decline everywhere, the level of development of systems on the east coast will actually decline, whereas the level of development of western systems increases. The implications of this finding are that eastern systems may become more resilient and reliable under this particular future climate scenario, whereas western systems may become less resilient and less reliable. This result assumes no adaptation or reallocation in the behavior of water supply systems. To determine the more realistic impacts of future climate change on water resource systems, additional GCM climate scenarios are required, and a more realistic model of the reallocations and adaptations that occur in real systems is required.
6. A comparison of Figs. 8 and 9 reveals that if a reservoir has a storage ratio in excess of unity it is dominated by over-year operations; however, if the storage ratio is less than unity, the reservoir is not necessarily dominated by over-year operations. The storage ratio, although commonly used to characterize overall reservoir operations, is not nearly as informative as other indices introduced here.

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