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ANALYSES OF RESERVOIR PERFORMANCE METRICS OF STREAMS, NEW JERSEY, USA

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Extended deficit analysis (EDA) is a useful procedure for estimating streamflow deficits and, hence, reservoir capacity for a given reliability of supply. In this study, EDA has been used to assess the 1 in 100 year deficit/reservoir capacity for a draft (demand) of 75% of the mean annual flow (MAF) for 30 unregulated streams in New Jersey, USA. The study demonstrates that for the same level of draft, streams draining northern catchments have relatively larger deficits and hence, higher storage capacities in comparison to those in the southern Coastal Plains. Three metrics, vulnerability, relative severity (also a measure of maximum number of years of water held in storage) and resilience have been used to assess stream reservoir performance (drought severity) for each of the 30 unregulated streams. An examination of the metrics revealed that drought in southern catchments could be less severe than those in the north for the chosen demand. It is proposed that higher hydraulic connectivity between groundwater and surface water (enhanced baseflow) for southern catchment streams may have been responsible for the observed trends in drought severity. Further, the study revealed that streams within the state could exhibit prolonged failure (drought) durations beyond a water supply level of 80% of MAF. Whilst annual vulnerability is predominantly related to stream interannual variability (measured by the coefficient of variation), the maximum number of years of water that can be held within a catchment at the given demand level (i.e. 0.75 MAF) is somewhat related to the lag-one serial correlation coefficient. This demonstrates that accurate replication of the coefficient of variation and the lag-one serial correlation coefficient in a streamflow time series could be paramount for appropriate prediction of future drought severity within the state. It is suggested that a water 'residence time' of at least a year could be combined with the lag-one serial correlation coefficient to characterize systems as predominantly carryover or within year systems for a given level of draft.

INTRODUCTION

New Jersey is the nation's most densely populated state (NJDEP, 1996). The population is expected to grow by 650,000 by the year 2010. As the population and the economic activity grow, so does the demand for water. Streams and rivers are important sources of water in New Jersey. Surface water supplies have become a very important source of water, especially in the northern part of the state essentially because of large rivers, favorable terrain and large population (groundwater is a major source of water for southern New Jersey). For example surface water resources (rivers and reservoirs fed by streams) represent 75% of water withdrawals from 1990 to 1996 (Hoffman, 2002). For drinking water supplies, 51% of the state population depends on surface water.

A report released in 2003 by the New Jersey Department of Environmental Protection (NJDEP) Water Supply Administration, noted that the states' population growth and regional population shifts have placed enormous additional demand on the water supply in many areas, especially during periods of drought (particularly, in geographic areas that have not previously experienced high water demand). For instance in 1995 and from 1997-2003 the state was forced to declare statewide or regional drought emergencies by issuing restrictions on water use. In particular, the states' stream gauging and groundwater monitoring networks during the 2002 drought year for instance indicated that some areas had the lowest stream flows ever recorded.

An appraisal of the surface water resources potential within the state in terms of identifying storage-yield (demand) relationships could be crucial to identifying the performance of surface water resource (streams) in space and in time. In particular, the magnitude of the return period of stream deficit could be very useful in planning for future water needs at a given demand level. An examination of the spatial distribution of stream reservoir performance metrics could also aid in delineating potential stress prone areas in the likely event of a drought. This information could be of help to water supply managers regarding resource allocation in times of drought.

In this study the extended deficit analysis (EDA), a reservoir storage-yield technique, is employed to estimate the 1 in 100 year streamflow deficits and, hence, reservoir capacity (needed) for a given reliability of supply. The analysis focuses on hypothetical storages at the stream gauging stations for each river and is restricted to a constant annual yield/draft (expressed as 75% of the mean annual flow) and a 99% reliability (1 in 100 recurrence interval) using the standard operating policy in which demand is satisfied if there is sufficient water in the reservoir, otherwise the reservoir empties. The purpose of this analysis is to evaluate the 1 in 100 year recurrence interval of streamflow deficit and hence reservoir capacity for all the rivers within catchments for the specified demand. The maximum deficit for each of the drainage basins concerned along with their recurrence interval is computed. It is proposed that the computed recurrence interval, T, for a given deficit/storage could serve as a guide for water supply managers on how often a deficit (of a given magnitude) is expected to occur, be equaled, or exceeded at the given level of demand. Further, three global reservoir performance metrics - vulnerability, resilience and relative severity - are used to compare drought characteristics within the north and southern portions of the state. Additionally, a characterization of streams based on within year and carryover tendencies are made to ascertain their relationship to reservoir performance metrics.

METHODS

Extended deficit analysis

The EDA proposed by Pegram (2000) is a simple technique for computing the average recurrence interval of reservoir deficit (the mean recurrence interval between emptiness) directly from the historical inflows excluding net evaporation and other losses. It is based on the premise that changes in stored water (where V is the deficit from the full condition) over time are equal to the difference between inflow volumes $Q(t)$ and outflow volumes $D(t)$ (demand or draft) of a reservoir, such that for any year;

$$V_{(t)} = \min\left(0, V_{(t-1)} + Q_{(t)} - D_t\right) \qquad (1)$$

For this notation a full reservoir occurs when V=0 and any excess water (any positive value of V) is considered to have spilled. $V(t)$ and $V(t\text{-}1)$ are storage (deficit; i.e. storage below full reservoir) values (≤ 0) at time t and t-1.

For constant water demand, $D(t)$ is set to D_o. In this paper, EDA was applied to annual streamflow and D_o is given by a constant value of 0.75 of MAF (mean annual flow). In applying EDA, the objective is to find the sequence of maximum deficits (largest negative values of V) between spill events. The reservoir is assumed to begin full (initial storage is assumed if V_o=0). The sequence of maximum deficits forms a renewal process (Feller, 1968) considered mutually independent given that they are separated by spills. It has been argued by Pegram (2000) that the larger deficits could be considered to follow a Gumbel (or type I extreme value) distribution. This follows from Troutman (1976) who argued that for a semi-infinite reservoir fed by a sequence of inflows with a draft less than the mean inflow (i.e. $\alpha < 1$) the maximum deficit was Gumbel. Once the series of deficits is obtained, they are ranked from the largest to the smallest. The average recurrence interval for each sample is calculated using the Gringortens' plotting position:

$$T = \frac{N + 0.12}{i - 0.44} \qquad (2)$$

where N is the number of years in the historical record and i is the rank of the deficit. The reduced Gumbel variate (y) is related to the average recurrence interval for a given deficit by Equation 4:

$$y = -\ln\left[-\ln\left(1 - \frac{1}{T}\right)\right] \qquad (3)$$

The EDA is applied in the current study because the method does not suffer from the limitation of defining reliability, as it does occur in the other semi-infinite reservoir techniques (McMahon and Mein, 1978). This is because the deficits are considered independent events rather than a sequence of dependent storage values formed from a sequence of flows into a semi-infinite reservoir (McMahon et al., 2007). Because the method is nonparametric in nature, it exploits the record in its entirety, in that it implicitly incorporates the basic record characteristics such as the mean, variability and serial correlation without having to extract statistics (McMahon et al., 2007). The method also has the advantage that it is able to estimate the storage needed to supply a given demand with a specified reliability.

Key reservoir characteristics

The three most widely used metrics in storage-yield analysis are active reservoir capacity S, draft or yield D, and reliability of draft, often expressed in terms of T, the average return period (in years) of at least one failure to supply the demand in an interval (month or year) (McMahon et al., 2007). Several measures of reservoir performance other than reliability are also used, namely vulnerability and resilience. To simplify theoretical analysis, active reservoir or storage capacity, which is defined as the difference between total storage capacity at full supply level and dead storage (the volume of water held below the lowest off-take) is used. The capacity is normally expressed as a ratio of mean annual inflow S/μ. This is a useful measure for practitioners because it represents the maximum number of years of water held in storage (McMahon et al., 2007). In this study this metric is used to compare the water storage capability for the catchments concerned. Draft, (demand) is usually expressed as a ratio of mean annual flow, $\alpha=D/\mu$, often as a percentage.

The standard net inflow m, or drift, which is commonly used as a rough criterion for classifying reservoirs as been dominated by within year or carryover systems is yet another parameter that involves draft. This is defined as:

$$m = \frac{1-\alpha}{Cv} \tag{4}$$

where $Cv=\sigma/\mu$ is the coefficient of variation of the annual inflow.

Two general classes of reservoir systems exist: over-year or carryover and within-year systems. Within-year systems are characterized by reservoirs which normally refill at the end of each year. Such systems are mainly sensitive to seasonal or daily variations in both the hydrological inflows and the system yield. For this system failure sequence will normally last only a few days or months. Over-year systems do not typically refill at the end of each year. For this system, failure may last years especially if demand curtailment programs are not implemented or no new water is imported (Vogel and McMahon, 1996).

Hazen (1914) was the first to use the standard drift parameter to analyze reservoir capacities for municipal water supplies. The parameter is also used to capture the impact of streamflow variability, Cv, and reservoir yield (α) on storage (McMahon et al., 2007). As a general rule, reservoirs with $m < 1$ operate predominantly as over–year or carryover storages and as within year systems if $m \geq 1$ (Vogel et al., 1995). Vogel et al. (1999) suggested that $m < Cv$ (over years storage) and $m \geq Cv$ (within year system) may be more appropriate. Montasari and Adeloye (2005) have argued that other variables in addition to m and Cv, such as reservoir performance indices (e.g., reliability), critical period and length of data record may be needed to classify reservoirs as predominantly within year or carryover systems. They argued for instance that a medium sized reservoir on a moderately variable stream (i.e. low Cv) may behave as a within-year system if the failure risk is high (low reliability) but may behave as an over-year system for a lower risk of failure. Since Equation (5) does not account for the additional aforementioned factors, Montasari and Adeloye (2005) argued that a complete test will be to estimate the length of the critical period and hence the extent of its departure from 12 months (a year). McMahon et al. (2007) employed the simple criteria of $m < 1$ and $m \geq 1$ ensuring that the critical period was at least a year.

In the current study the serial correlation coefficient (whose magnitude increases with the strength of carryover effects within a catchment) as well as S/μ (surrogate of water residence time, in years) is used as a first approximation to discriminating between predominantly within year or carryover systems. In this case it is ensured that the critical period is at least a year at the given level of reliability (McMahon et al., 2007). The idea is that the time dependent structure of a streamflow time series (measured by the serial correlation coefficient, r_1) is the result of fluctuation of storage at the end of a planning year in comparison to the annual mean (Salas et al., 1988). When negligible changes in the total water stored in a basin occur at the end of each water year, the series is deemed independent. In this case, the variations in the annual streamflow, for instance, in the present time (year) have minimal or no direct (temporal) bearing on flow in previous years. On the other hand, the streamflow time series is considered dependent (i.e. statistically significant r_1) when there is large fluctuation in storage in comparison to the mean. Thus the likelihood of a higher variability streams showing carryover tendencies are higher than lower variability ones. This assertion is in general agreement with the definition of m in Equation (4). Thus, r_1 could be regarded as a consequence of the magnitude of the 'residence time', S/μ . In comparing the two metrics; $S/\mu \geq 1$ and a statistically significant r_1 (significance level of 95%) is adopted as a criterion for predominantly carryover streams. The serial correlation coefficient was computed using the statistical package for the social sciences (SPSS, 2005) version 14 software. A significance level of 95% was chosen as a basis for deciding whether or not computed r_1 values did occur by chance. It is important to mention here that in this paper, the storage capacity (S/μ) also referred to as the relative severity by Peel et al. (2005) to characterize drought severity, is used interchangeably with 'residence time' (maximum number of years of water held in storage).

Reservoir vulnerability

Vulnerability seeks to measure the severity or the extent of the failure of a reservoir to meet a target draft (in this case a draft of 75% of the mean annual flow). The metric measures the average volumetric severity of failure during a failure period and has been defined by Hashimoto et al. (1982) as;

$$\eta' = \frac{\sum_{k=1}^{f_s} \max \cdot (sh_k)}{f_s} \tag{5}$$

where η' is the vulnerability, $\max(sh_k)$ is maximum shortfall during the kth continuous failure sequence, and f_s is the number of continuous failure sequences in the simulation. Normally, the vulnerability is expressed in dimensionless units by dividing by the target demand during the failure period. This is denoted by:

$$\eta = \frac{\eta'}{D} \tag{6}$$

where η is the dimensionless vulnerability and D the target demand during failure.

Reservoir resilience

This metric defines how quickly a system recovers from a failure. Several definitions of resilience have been used in the literature (Fiering, 1982). The most widely used definition is that due to Hashimoto et al. (1982). In the context of Hashimoto et al. (1982) resilience is the probability that a reservoir system would recover following failure. This is expressed as in Equation 7:

$$\varphi = \frac{1}{\left(f_d / f_s\right)} = f_s / f_d \; ; \; f_d \neq 0 \tag{7}$$

where φ is resilience, f_s is the number of individual continuous sequence of failure periods, and f_d is the total duration of failures. The longer the average duration of failure, either due to a longer f_s or a fewer failure sequences, the smaller is the resilience and hence the more difficult would a reservoir tend to recover from failure. Consequently, within-year systems will have higher resilience than the over-year systems (Montesari and Adeloye, 1999). According to Hashimoto et al. (1982) the resilience is the probability of a year of success following a year of failure.

Study area and data

The streams used in this analysis were obtained from the United States Geological Survey (USGS) National Water Information System (NWIS) web site. The mean daily stream flows were aggregated into annual totals (based on water year). Stations were selected based on the following two criteria;

1. gages with more than 25 years of data (with at most 2 years of missing data);

2. gages that were considered unregulated as defined by Watson et al. (2005). Thirty streams meet this criterion.

The criterion for 1 above is based on the fact that the study seeks to compute steady state reliability of at least 95% (at least a 1 in 20 probability of failure). In particular deficits were computed for a return period 100 years. The second criterion is to ensure that streams have little or no diversions upstream and thus represents natural flows. Figure 1 shows the locations of streams gauges used in the study.

RESULTS AND DISCUSSIONS

Storage capacity/deficit

Table 1 shows the hydrological parameters analyzed. Due to parsimony of space only storage capacity based on deficit for a draft, $\alpha = 0.75$ is shown in Table 1. Also shown in Table 1 are the standardized drift parameter *m* and the storage capacity for all catchments categorized according to physiographic regions. Highlands and Valley and Ridge provinces are treated together because of their geological similarity and small number of gauges. The 1 in 100 year deficit (for a draft of 0.75) across the state ranged from 0.67×10^6 m^3 (station # 01466500) to 234.03×10^6 m^3 (station # 01400000). Thus on average, one expects a reservoir storage capacity of 0.67×10^6 m^3 and 234.03×10^6 m^3 to provide a draft of 75% (of MAF) with a reliability of supply of 99% at station numbers 01466500 and 01400000 respectively. Also shown in Table 1 is the average recurrence interval of the maximum deficit for each of the stations analyzed. It is clear from Table 1 that for the same level of reliability streams draining northern catchments (Highlands, Piedmont and Valley and Ridge provinces) generally have higher deficits and hence require higher storage capacity to supply the given draft (i.e., 0.75 of MAF) in comparison to southern coastal plains streams. The coastal plain is primarily composed of sandy soils through which water infiltrates very quickly into the groundwater reservoir and hence input from precipitation plays a very small role in surface water storage unless a confining layer is present (Newell et al., 2000). Due to high slopes and thin soils in the northern physiographic provinces, much of the surface water input from precipitation plays a major role in the storage capability of streams. As a consequence, it is

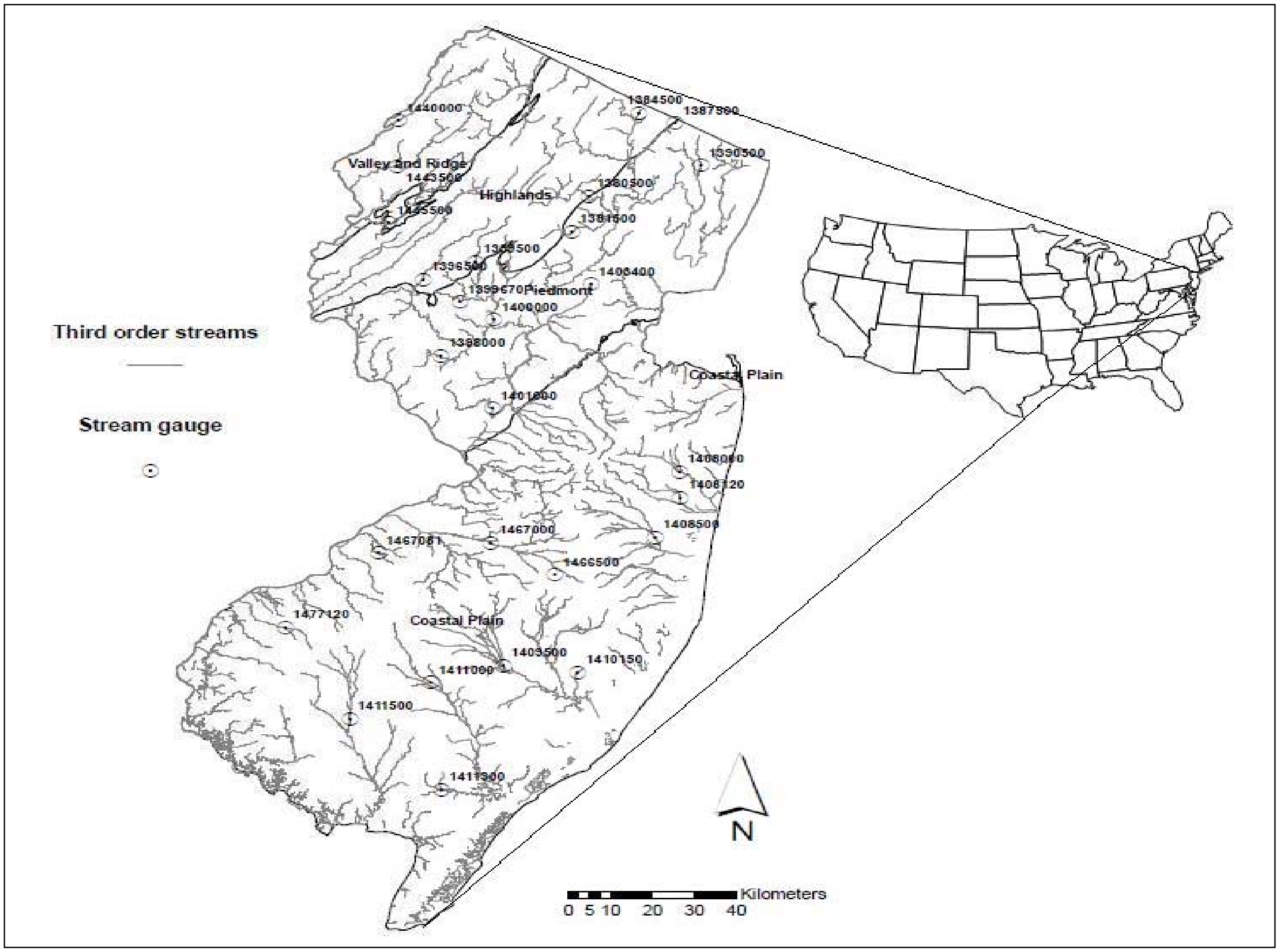

Figure 1. A map of the study area showing the streams used in this study.

expected that the maximum number of years of surface water held in storage for northern catchments will be relatively higher than those of the southern coastal plain (see Table 1 for the metric S/μ). Conversely, in terms of storage deficit (i.e. using the definition of Peel et al., 2005), this would imply that streams within northern catchments would experience relatively more severe drought should it occur.

Figure 2 shows the number of independent deficits for the 30 unregulated rivers ($N \geq 25$, for $\alpha = 0.75$) compared with record length. For the choice of parameters, the best fit lines for the north

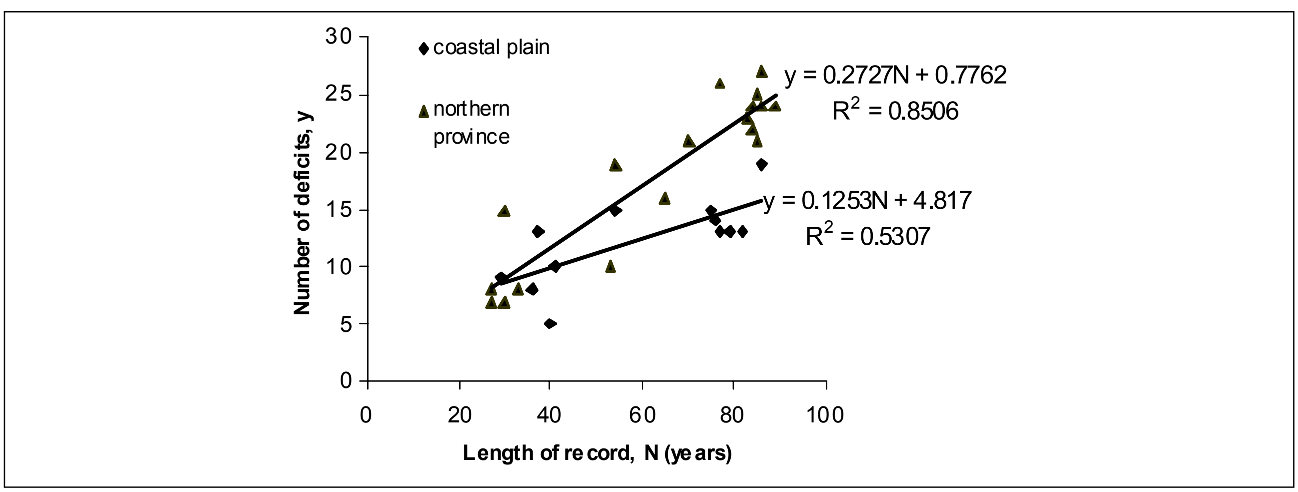

Figure 2. Length of streamflow data versus maximum number of deficit for a draft of 0.75.

Table 1. Statistical characteristics of the streams used in the study.

Station #	Station name	Province	N	Mean flow Mm^3	Cv	m	Max. Storage Mm^3	1 in 100 Mm^3 Storage/ Deficit	T_{max}	η	S/μ	φ	Cs	r_1	P Val.
01467081	South Branch Pennsauken Creek at Cherry Hill	CP	40	16.8	0.24	1.1	3.49	4.0	66	0.15	0.2	1.00	0.16	-0.44	0.78
01408000	Manasquan River at Squankum	CP	76	65.9	0.26	1.0	20.93	19.0	136	0.17	0.3	0.71	0.33	0.20	0.08
01408120	North Branch Metedeconk River near Lakewood	CP	36	54.1	0.27	0.9	14.95	19.0	45	0.19	0.4	0.75	0.08	-0.04	0.92
01408500	Toms River near Toms River	CP	79	188.7	0.23	1.1	42.64	40.1	141	0.12	0.2	0.77	0.35	0.21	0.06
01409500	Batsto River at Batsto	CP	77	107.5	0.23	1.1	30.00	28.8	138	0.17	0.3	0.69	0.09	0.17	0.14
01410150	East Branch Bass River near New Gretna	C P	29	14.5	0.24	1.0	4.43	5.1	65	0.17	0.4	0.44	0.17	0.09	0.64
01411000	Great Egg Harbor River at Folsom	CP	82	76.3	0.23	1.1	27.03	26.7	103	0.18	0.3	0.77	0.01	0.21	0.06
01411300	Tuckahoe River at head of River	C P	37	37.3	0.32	0.8	11.91	13.9	57	0.17	0.4	0.77	0.23	0.07	0.67
01466500	Mcdonalds Branch in Byme state forestXXX	CP	54	1.9	0.29	0.9	0.60	0.7	66	0.23	0.4	0.53	0.62	0.19	0.15
01467000	North Branch Rancocas Creek	C P	86	151.9	0.26	1.0	52.34	48.7	154	0.16	0.3	0.74	0.32	0.13	0.21
01477120	Raccoon Creek near Swedesboro	CP	41	35.7	0.28	0.9	12.07	13.0	77	0.17	0.4	0.90	-0.02	0.06	0.64
01411500	Maurice River at Normal	C P	75	146.0	0.26	1.0	44.55	45.1	96	0.22	0.3	0.67	-0.02	0.18	0.11
01399500	Lamington (black) River near Pottersville	HL	83	49.9	0.29	0.9	47.64	47.6	100	0.28	1.0	0.52	0.36	0.02	0.02
01380500	Rockaway River above reservoir at Boonton	HL	70	206.4	0.29	0.9	215.9	2.5.9		0.29	1.0	0.52	0.06	0.31	0.01
01396500	South Branch Raritan River near High Bridge	HL	89	109.9	0.28	0.9	90.84	82.7	138	0.25	0.8	0.46	0.29	0.32	0.02
01445500	Pequest River at Pequest	HL	86	142.1	0.32	0.8	194.28	195.4	97	0.36	1.4	0.41	0.16	0.28	0.01
01384500	Ringwood Creek near Wanaque	HL	65	30.0	0.27	0.9	25.24	24.0	117	0.30	0.8	0.50	-0.08	0.22	0.08
01443500	Paulins Kill at Blairstown	VR	85	179.1	0.29	0.9	198.35	212.5	79	0.34	1.2	0.52	0.31	0.25	0.02
01440000	Flat Brook near Flatbrookville	V R	84	99.9	0.28	1.0	83.47	81.3	109	0.20	0.8	0.45	0.32	0.19	0.07
01403540	Stony Brook at Watchung	PD	33	9.0	0.29	0.8	3.20	3.7	60	0.35	0.4	0.75	-0.01	-0.11	0.51

PD =Piedmont; CP=Coastal Plain; VR=Valley & Ridge, HL=Highlands; T_{max}= return period corresponding to maximum deficit

and south physiographic province can be represented respectively by $y = 0.2727\ N + 0.7762$; and $y = 0.1253\ N + 4.817$ (where y represents the deficits and N is the number of years of record). Figure 2 illustrates that there is a relatively strong and positive relationship between the number of deficits and record length. For the southern coastal plain, the record length explained 53% of

Table 1. Statistical characteristics of the streams used in the study (continued).

Station #	Station name	Province	N	Mean flow Mm^3	Cv	m	Max. Storage Mm^3	1 in 100 Mm^3 Storage/ Deficit	T_{max}	η	S/μ	φ	Cs	r_1	P Val.
01390500	Saddle river at Ridgewood	PD	53	30.5	0.30	0.9	10.87	13.4	45	0.25	0.4	0.60	0.18	0.14	0.30
01381500	Whippany River at Morriston	PD	86	34.3	0.29	0.9	37.33	45.4	42	0.21	1.3	0.50	0.42	0.33	0.00
01387500	Ramapo River near Mahwah	PD	85	200.6	0.28	0.7	106.72	100.0	125	0.36	0.5	0.67	0.11	0.07	0.52
01398000	Neshanic River near Reaville	PD	77	60.6	0.37	0.6	36.49	37.6	89	0.49	0.6	0.54	0.36	0.10	0.33
01399670	South B Rockaway Creek at Whitehouse station	PD	30	26.4	0.44	0.7	13.23	17.2	28	0.39	0.7	0.20	1.27	0.09	0.57
01401000	Stony Brook at Princeton	PD	54	60.6	0.36	0.8	49.58	43.2	186	0.34	0.7	0.53	0.10	0.07	0.59
01403400	Green Brook at Seeley Mills	PD	27	43.1	0.31	0.8	4.12	5.1	50	0.32	0.1	0.57	-0.04	0.05	0.79
01400000	North branch Raritan River near Raritan	PD	84	279.6	0.30	0.8	245.33	234.0	186	0.28	0.8	0.46	0.35	0.19	0.07
01401650	Pike Run at Belle Mead	PD	27	9.1	0.35	0.7	4.41	5.5	47	0.41	0.6	0.50	-0.23	-0.15	0.43
01396660	Mulhockaway Creek at Van Syckel	PD	30	18.03	0.31	0.8	5.7	6.6	54	0.23	0.32	1.00	0.35	-0.05	0.77

PD =Piedmont; CP=Coastal Plain; VR=Valley & Ridge, HL=Highlands; T_{max}= return period corresponding to maximum deficit

the variance in streamflow deficit whilst for the northern provinces it explained 85% of the variance in streamflow deficit.

Vulnerability, Relative Severity and Resilience

Figures 3, 4 and 5 show the spatial distribution of stream vulnerability, relative severity, and resilience across the state. The trend in spatial distribution of the relative severity (relative to the mean) is similar to trends in vulnerability. The similarity of the two metrics (vulnerability and relative severity) is a manifestation of the fact that each of these metrics can be used to characterize drought severity for streams within the state. The computed vulnerability for the coastal plain, Piedmont and Highlands (including the Valley & Ridge) are respectively 0.17, 0.28 and 0.31. This implies that the severity of failure of southern catchment streams to meet the target draft (draft of 75%) may be a direct consequence of the 'minimal' shortfalls within the simulation. On average, the proportion of time (individual time) within the simulation period where the target draft was not met for the north and south were respectively 0.3 and 0.2 respectively. Similarly, the proportions of continuous time of failure within the simulation period were found to be similar for both regions (0.15 and 0.16 for north and south respectively). Due to the similarity in the time of failure periods for the north and southern provinces, a comparison is made between the proportions of (continuous) time of failure versus vulnerability. The proportion of the time of failure was chosen in order to eliminate biases in vulnerability due to record length (i.e., by dividing failure periods by length of time series).

The analysis showed that for southern catchments, vulnerability is independent of the proportion of time of continuous failure. That is, the relationships between the proportion of time of continuous failures and vulnerability was not statistically significant at the 95% confidence limit and explains only 0.08% of the variance. On the contrary, a similar analysis for northern streams

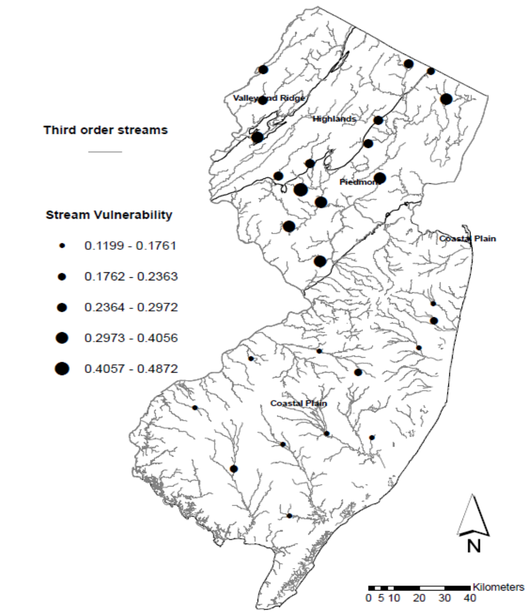

Figure 3. Spatial distribution of stream vulnerability.

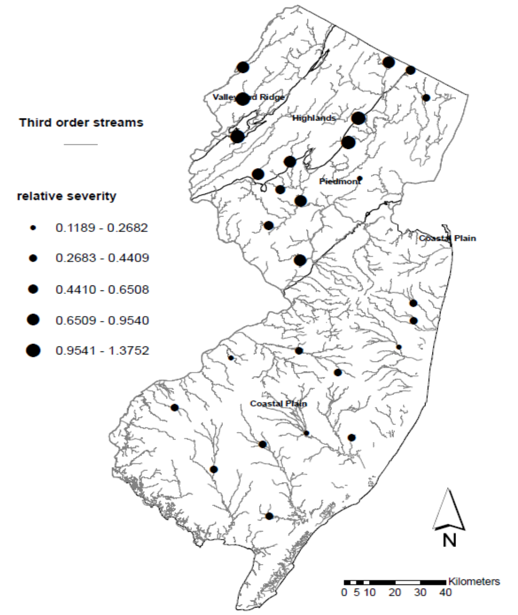

Figure 4. Spatial distribution of relative severity (storage capacity).

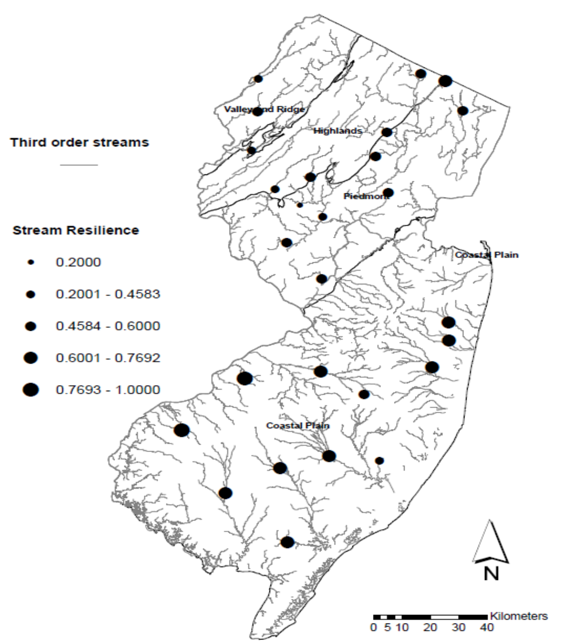

Figure 5. Map showing the distribution of stream resilience.

indicated statistically significant (at the 5% level) relationships between the metrics, and explains 51% of the variance (see Figure 6). Again, the maximum shortfall (not significant) accounts for less than ~0.0002% of the variation in vulnerability for northern streams. This phenomenon is a manifestation of the fact that streams in this province have a greater propensity for exhibiting carryover tendencies (see discussion under "characterization of within year and carryover systems"). For the southern streams the maximum shortfall (maximum cumulative deficit) explained ~22% (not shown) of the variation in vulnerability. The above observations suggests that the vulnerability of northern streams is greatly influenced by the number of continuous failure periods. Put differently, the perceived higher vulnerabilty for northern catchment streams is more

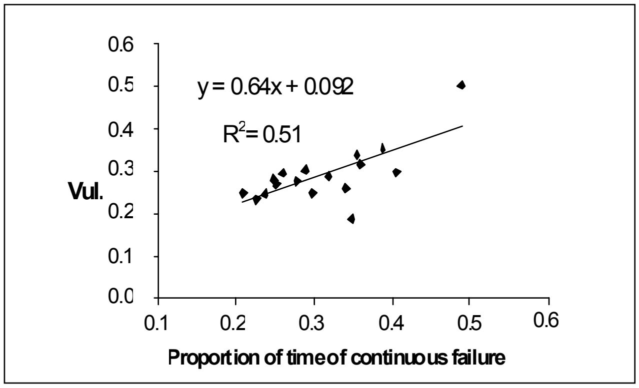

Figure 6. A plot of the proportion of time of failure versus vulnerability (Vul.) for northern streams.

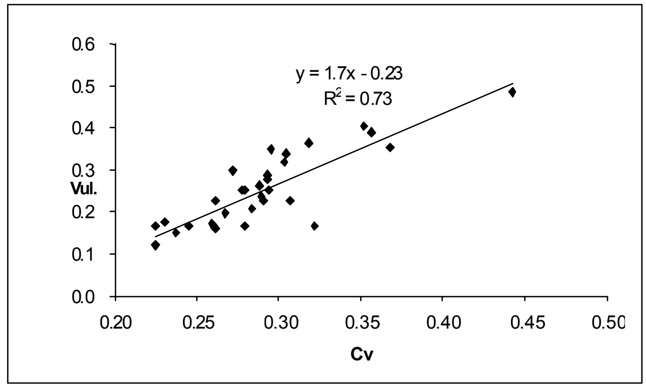

Figure 7. Relationship between Cv versus vulnerability.

of a consequence of the frequency of times the reservoir runs below the stipulated demand level and to a lesser extent the magnitude of the deficit itself. This phenomenon for southern catchment streams, the severity of the shortfall (η) is probably more of a consequence of the maximum shortfalls (see Equation 6) rather than the continuous time of failure.

The lower vulnerability of southern catchment streams may be the result of the fact that during lowflow periods (periods where streams normally fail to meet target demand) a substantial amount of groundwater supplements surface water storage in the coastal plain catchments. It is possible that the high hydraulic connectivity between surface and groundwater in southern catchments (NJDEP, 1996) may have accounted for the relative lower vulnerability) in comparison to northern streams. This observation is in agreement with previous studies (Xeflide and Ophori, 2008) which indicated that coastal plain streams are largely fed by groundwater during lowflow regimes. In order to ascertain whether or not baseflow indeed may have played a role in the relative disparity in vulnerability across the two main regions of the state, streamflow resilience (ability of the streamflow to recover after failure) was compared. The assumption used here is that streams fed by a relatively larger amount of baseflow have a greater ease of recovery from failure. Southern catchment streams have a higher probability of recovery from failure (mean φ is 0.73) in comparison to northern streams ($\varphi = 0.51$) (See Figure 5) (i.e. the probability of a year of success following a year of failure/drought is greater for southern catchment streams). The relationship between vulnerability, Cv, Cs, and r_1 within the state was also explored using a regression analysis. The relationship between vulnerability and Cv are statistically significant at the 5% confidence level, explaining 73% of the variance (Figure 7). The importance of the coefficient of skewness Cs and lag-one autocorrelation r_1 to the vulnerability was accessed after the influence of interannual variability, Cv, was removed by calculating the residuals of the relationship between vulnerability and Cv respectively (not shown). The relationship between the residual vulnerability and the coefficient of skewness is insignificant at the 5% level. This implies that the interannual variability of streamflow is the predominant influence on stream vulnerability. The results agree with previous studies (e.g., Heathcote, 2000; Peel et al., 2005).

Further, it is noted that moderate variability streams (the computed average annual Cv for the south and north is 0.26 and 0.31 respectively) such as those under study, characteristically experience relatively lower drought (in comparison to higher variability ones) (Peel et al., 2005). Based on this premise, it is noted that the lower vulnerability and lower relative severity of the coastal plain streams is a consequence of lower interannual variability.

The relative severity S/μ and annual r_1 are statistically significant at the 5% level, explaining 26% of the variance. The importance of the coefficient of skewness Cs and Cv to relative severity was assessed after the influence of r_1 was removed by calculating the residuals of the relationship between S/μ and r_1. The relationships between residual S/μ and Cv were significant at the 5% (significance) level, explaining 16% of the variance. The coefficient of skewness is insignificant at the 5% level. The moderate significant relationship between S/μ and r_1 underscores the influence of the strength of carryover effect on lag-one serial correlation coefficient. The importance of the two metrics, Cv and r_1 on drought related metrics has some research and policy implications. Firstly, variability and lag-one serial correlation coefficient are more important than averages in predicting future extreme drought events. Secondly, accurate replication of interannual variability and the lag-one serial correlation coefficient would be very important in modeling and predicting of drought magnitude and severity.

Characterization of within year versus carryover systems.

On the basis of the standard drift parameter (m) alone, it is noted that all the streams draining northern catchments have predominantly carryover tendencies (inability of streams to deliver the target draft could last for years) for a draft of 75%. Similarly 67% of southern catchment streams exhibit carryover tendencies. The relative higher propensity for carryover tendencies of northern catchment streams could be traced to longer failure duration. An analysis of m based on various values of drafts (not shown) indicates that at a demand level of 60% and below ($a \leq 0.60$) all streams show predominantly within year tendencies. Similarly for a demand of 80% and above ($a \geq 0.80$) all streams show predominantly carryover tendencies. This suggests that streams within the state could exhibit prolonged failure durations beyond a water supply level of 80% MAF.

Using the definition of Vogel et al. (1999) it is seen that streams analyzed show predominantly within year tendencies for a draft of 75%. The above two criteria confirms the argument by Montesera and Adeloye (2005) that Cv and m alone are insufficient for completely characterizing streams as over-year or within year systems. In particular, since streams within the study region are low variability ones (Xeflide and Ophori, 2008), the computed standardized drift parameter (inverse of Cv) is expectedly high especially for lower draft. This phenomenon results in carryover tendencies according to the criteria of McMahon et al. (2007). Similarly, the low inter-annual stream variability means a higher probability of streams having $m > Cv$. In the current paper it is suggested that for low variability streams, the lag-one serial correlation coefficient and the "residence time" (i.e. S/μ) could also be used for characterizing streams as predominantly within year or carryover systems. Evidently, from Table 1 it is seen that all streams (except stream with gauge #01396500) with water "residence time" of at least a year have a significant lag-one serial correlation coefficient. As noted in the previous section, the residence time is found to be somewhat related to r_1. In this paper the two metrics are used as a first approximation in characterizing streams as exhibiting predominantly either within year or carryover tendencies. It is important to mention however that the residence time varies with the level of draft. These streams show predominantly carryover tendencies; water stored in a given year is carried into the following year. All streams showing significant carryover capacity are within the northern catchments. It is noted that systems dominated by carryover storage requirement are less likely to recover from failure than systems dominated by within-year storage requirements. This explains why streams within southern catchments are relatively more resilient.

CONCLUSIONS

Reservoir storage capacity/deficit has been investigated using extended deficit analysis. The study indicated that the 1 in 100 year deficit, and, hence the storage capacities of northern catchment streams are much higher than those in the south. Three other metrics, stream vulnerability, relative severity and resilience have been used to characterize drought within the state of New Jersey. The spatial distribution of both stream vulnerability and relative severity were found to be similar; relatively higher in northern catchment streams in comparison to the southern coastal plain. The higher vulnerability in northern catchments may be due to the relative lower degree of baseflow to those streams in comparison to their southern counterparts. This is also reflected in a higher probability of recovery of southern streams (higher resilience) in the event of a drought. The relatively lower interannual variability of southern streams has also been identified as the probable cause for their lower vulnerability. The statewide streamflow vulnerability is found to be predominantly related to the interannual variability (measured by Cv) and to a lesser extent the coefficient of skewness. Further, it is noted that streams with a "residence time" of at least a year display statistically significant lag-one serial correlation coefficients. The study proposes that the two metrics could be used as a first approximation to characterizing streams as exhibiting predominantly over year or within year tendencies. Further it is suggested that streams within the state could exhibit prolonged failure (drought) durations beyond a water supply level to level of 80% MAF.

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