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Construction of Storage–Performance–Yield Relationships for a Reservoir Using Stochastic Simulation

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ABSTRACT *In the past, many researchers have used stochastic streamflow models along with sequent peak algorithm or simulation to obtain storage–reliability–yield (S–R–Y) relationships for a reservoir. These S–R–Y relationships consider only the probability of failure, but not the likely consequences of the failure (vulnerability). In this paper, separate contours of reservoir performance, namely reliability and vulnerability (event-based), have been developed on the storage–yield plane, using stochastic reservoir simulation. These contours of performance, when superposed, give rise to the storage–performance–yield (S–P–Y) relationships, the construction of which is illustrated in this paper through a case example. These relationships provide more comprehensive information to the reservoir planner regarding performance than the S–R–Y relationships.*

Introduction

The storage–yield relationship determined from historical data using either Rippl's mass curve or its automated equivalent, namely sequent peak algorithm, was traditionally used to find the storage capacity of a reservoir by hydrologists and water resources planners all over the world, prior to the advent of stochastic streamflow models. Even now, in most countries, the same traditional practice is in vogue, since many of the practising engineers are either not aware of the merits of using the stochastic models for making better decisions, or have not been able to accept the stochastic line of thinking. The stochastic streamflow models provide a large number of similar sequences which can be used to estimate the reliability with which a storage reservoir can deliver pre-scheduled quantities of water. The probability distribution of the required storage capacity (K) of a reservoir to supply a prespecified release has been derived using stochastic streamflow models by Fiering (1967), Wallis & Matalas (1972), Klemes *et al.* (1981), Vogel (1985), Vogel & Stedinger (1987) and a host of other researchers in the past. The cumulative distribution function of K characterizes the relationship between the required storage capacity to meet a pre-specified yield and the probability of a failure-free (safe) operation over a planning horizon of N years. This probability denotes the reliability with which a reservoir of size K will provide failure-free operation over the planning period. A variety of annual and periodic stochastic models have been employed by various researchers (Lawrence & Kottegoda, 1977; Hirsch, 1979; Klemes *et al.*,

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1981; Stedinger & Taylor, 1982a, 1982b; Stedinger *et al.*, 1985; Vogel & Stedinger, 1987) to find the storage–reliability–yield (S–R–Y) relationships using sequent peak algorithm (either single or double cycling). The S–R–Y relationships are useful for water resources planners to make meaningful decisions when compared with the decisions based on a single estimate of reservoir capacity from historical sequence. However, these relationships do not consider the likely consequences of the possible failures. Vogel (1987) introduced the concept of reliability indices for water supply systems, drawing analogy from the design of hydraulic structures for flood control. Further, Vogel & Stedinger (1987) have developed generalized approximate S–R–Y relationships for the realistic situation when annual streamflows belong to a two-parameter log-normal distribution and the logarithms of flow follow a first-order autoregressive model. Further, Vogel & Stedinger (1988) have clearly shown the usefulness of stochastic streamflow models in determining over-year reservoir storage capacity estimates. Their study recognizes and attempts to quantify sampling variabilities in estimating the storage capacity quantiles, apart from establishing the superiority of using stochastic flows instead of the single historical record in reservoir design applications.

In general, reliability is defined as the ratio of number of times the reservoir system was successfully operated to the total number of times it has been operated. Here, successful operation refers to meeting the target demand with the storage that would be available in the reservoir. This is the most commonly used measure of performance in reservoir planning and operation. It is to be noted that reliability is indicative of only the frequency of deficit and not the magnitude.

In addition to reliability, two more performance indicators, namely resilience and vulnerability, have been defined by Hashimoto *et al.* (1982). Resilience refers to 'how quickly the system returns to a satisfactory (normal) state once a failure has occurred' and vulnerability signifies the likely consequences of severe failures. Even when the probability of failure is small, the possible consequences of failure are to be taken care of. When the system is able to perform to a desirable level of reliability, then, it will be wiser to expend efforts in reducing the severity of failure (vulnerability) than attempting to increase marginally the reliability or totally eliminate the failure. All these system performance indicators together characterize the stochastic and dynamic performance of reservoir systems in a more complete manner. Loucks *et al.* (1981) have described the usefulness of performance indicators with the help of a simple, hypothetical example in which a two-season reservoir provides water for irrigation during summer. The simulation of reservoir operations was done with 25 replicates of 20-year long synthetic flow sequences generated with a Thomas–Fiering model. Hashimoto *et al.* (1982) have employed a stochastic dynamic programming model for the same two-season problem given by Loucks *et al.* (1981), to derive a range of operating policies with the objective of minimizing the expected losses (related to the three performance criteria). They have concluded that: (i) realistic operating policies possess high reliability, modest resilience and low vulnerability and (ii) the maximum possible reliability (or resilience) do not coexist with the minimum vulnerability. Moy *et al.* (1986) formulated a multi-objective optimization model using mixed-integer programming to find out the trade-off relationships between the performance indicators.

Proposed Study

In this paper, it is envisaged to develop contours of two important performance indicators, namely reliability and vulnerability, on the storage–yield plane of the reservoir considered which, when superposed, result in 'storage–performance–yield' (S–P–Y) relationships, forming an extension of the S–R–Y relationships already in use. The S–P–Y relationships would be useful for reservoir planners to evaluate the required storage capacity for a desired combination of reliability and vulnerability. This attempt is made recognizing the importance of the complete stochastic and dynamic description of 'risk and consequence' of failures even at the planning stage. For the construction of these performance contours, performance information is to be obtained at very close intervals in the desired ranges of storage and yield. The S–P–Y relationships referred to would form a comprehensive decision-aid to reservoir planners. The construction of the S–P–Y relationships and their usefulness have been illustrated through a case example of an existing irrigation reservoir in Southern India.

In this paper, the following operational definitions are adopted for the performance indicators:

- *Reliability* is defined as the ratio of the number of times the target demand is satisfied to the total number of times the reservoir is operated.
- *Vulnerability* is defined as the 'maximum event deficit volume' encountered within the entire period of operation. Here, 'event deficit' refers to the cumulative deficit from the start of a failure to the end of that failure event (till the system recovers from failure). This means that a failure event may have one or more consecutive failure periods. Especially when there is more than a single period having severe deficit within a failure event, the maximum event deficit would be a better indicator of the magnitude of failure than simply using the maximum single period deficit as the indicator (as done by earlier investigators). The vulnerability based on 'event deficit' will be very well suited for irrigation systems.

Stochastic Simulation Using Standard Operating Policy

The reservoir simulation model used in this paper is composed of the storage-continuity constraints and the standard operating policy. The standard operating policy is a simple, realistic and prevalently used policy of a reservoir which aims to satisfy the target demand, if sufficient water is available, and if not, to supply whatever is available. Klemes (1977) has shown that an optimal policy converges to the standard operating policy as either hydrologic or economic uncertainty grows. In fact, the standard operating policy is known to yield reasonably high reliability and resilience, low vulnerability and moderate mean deficit. Hence the same has been used in this study for constructing the S–P–Y relationships.

If τ is the season and v is the year, then the actual release in each season $R_{v\tau}$ is determined from the following relation:

$$R_{v\tau} = \begin{cases} S_{v\tau} + Q_{v\tau} - E_{v\tau} - K, & \text{if } (S_{v\tau} + Q_{v\tau} - E_{v\tau} - D_{v\tau}) > K \\ D_{v\tau}, & \text{if } K \geq (S_{v\tau} + Q_{v\tau} - E_{v\tau} - D_{v\tau}) \geq 0 \\ (S_{v\tau} + Q_{v\tau} - E_{v\tau}) & \text{otherwise} \end{cases} \tag{1}$$

where $S_{v\tau}$ is the initial storage, $Q_{v\tau}$ is the inflow, $E_{v\tau}$ is the evaporation volume, $D_{v\tau}$ is the target demand, $R_{v\tau}$ is the actual release and K is the active storage capacity of the reservoir. Then, the storage in the reservoir at the beginning of the $(\tau+1)$th season (which is equal to the storage at the end of the τth season) is:

$$S_{v(\tau+1)} = S_{v\tau} + Q_{v\tau} - R_{v\tau} - E_{v\tau} \tag{2}$$

Here, the evaporation loss has been computed as a function of the initial storage of the month, without much loss in accuracy, in order to avoid iterative computations (Haktanir, 1989). It is also possible more rigorously to consider evaporation to be a function of the average of the beginning- and end-of-month storages. But this needs an iterative scheme to be solved for each period (month) of operation, and this may not be worthwhile (especially if this has to be done for all the synthetic sequences generated), for the accuracy achieved in the computation of performance indicators.

Model Fitting and Verification

Often, the monthly or weekly hydrologic time series display a periodic correlation structure. Hence, it is preferable to consider periodic autoregressive (PAR) models or periodic autoregressive moving average (PARMA) models, which are known to preserve the periodic correlations well, in case of reservoir systems which fill each year, wherein the within-year effects are predominant. An added advantage of these periodic models is that the parameters of each period can be estimated independently of the other periods.

Periodic Autoregressive (PAR) Model

The general structure of the PAR model is given by:

$$Z_{v,\tau} = \sum_{j=1}^{p} \phi_{j,\tau} Z_{v,(\tau-j)} + \varepsilon_{v,\tau} \tag{3}$$

where the subscripts v and τ denote the year and the period, respectively, p denotes the order of the model, $\{Z_{v,\tau}\}$ is the time series suitably transformed and standardized and has an expected value equal to zero, $\phi_{j,\tau}$ are the autoregressive parameters and $\{\varepsilon_{v,\tau}\}$ is the error or noise term assumed to be uncorrelated. Quite often, it may be sufficient to go in for an order $p=1$ or 2 (PAR(1) or PAR(2)), and p may be assumed to be the same for all the periods. Change in the order 'p' between the periods is not considered in the stochastic modelling done in this paper.

Periodic Autoregressive Moving Average (PARMA) Model

The general structure of the PARMA model is given by:

$$Z_{v,\tau} = \sum_{j=1}^{p} \phi_{j,\tau} Z_{v,(\tau-j)} + \varepsilon_{v,\tau} - \sum_{j=1}^{q} \theta_{j,\tau} \varepsilon_{v,(\tau-j)} \tag{4}$$

where $\theta_{j,\tau}$ are the moving average parameters, and the other notations are the same as explained for PAR models.

For the PAR and PARMA models described, the three-step modelling procedure suggested by Box & Jenkins (1976) is followed. The identification of the periodic model is done by inspecting the historical and the transformed flow series, the basic periodic statistics including the period to period serial correlations, the autocorrelation function (ACF) and the partial autocorrelation function (PACF) plots of historical as well as transformed flows. The parameter estimation has been done by the method of moments (MOM) (Salas *et al.*, 1980, 1982). The diagnostic checking of residuals consists of: tests for independence (modified Anderson test, plot of ACF of residuals); test for normality, skewness test for individual periods. The verification is intended to reproduce the basic statistics of the historical flows at the periodic level, namely, periodic means, periodic standard deviations and periodic correlations.

Construction of S–P–Y Relationships

The steps involved in constructing the S–P–Y relationships are:

(1) Routeing the entire number of periodic synthetic sequences generated (using the periodic stochastic model fitted) through the reservoir of an assumed capacity to satisfy a prespecified periodic target demand under a standard operating policy, thus simulating the possible future operations. The mean and the standard deviation of the performance indicators, computed from the simulated operation of the reservoir for the prespecified capacity and the demand pattern, are tabulated.

(2) The performance indicators are also computed for a number of other reasonable capacities and target demands, at close intervals. Thus, comprehensive information regarding performance on the storage–yield plane would be obtained for the reservoir.

(3) This entire information regarding the performance criteria on the storage–yield plane is used to obtain the respective performance contours. Points of equal reliability, plotted on the storage–yield plane, are joined to get the contours for reliability; and points of equal vulnerability (maximum event deficit) are joined to obtain contours for vulnerability.

(4) The two performance contours are finally superposed to obtain the required S–P–Y relationships.

Such S–P–Y relationships can also be obtained for optimal operating policy or other practical policies, following steps (1) to (4) above.

Computer Program 'SPY'

A computer program 'SPY' is written in Fortran 77, which fits low-order periodic stochastic streamflow models (PAR/PARMA models with a set of commonly used transformations and a Thomas–Fiering log-normal 3-parameter model with three different options), generates periodic synthetic sequences, verifies the basic periodic statistics, routes the generated periodic synthetic flow sequences through the reservoir using a periodic simulation model based on standard operating policy and evaluates the performance in terms of reliability and vulnerability (maximum event deficit). The information obtained regarding performance criteria is plotted on the storage–yield plane. The logic of the program SPY is given in Figure 1.

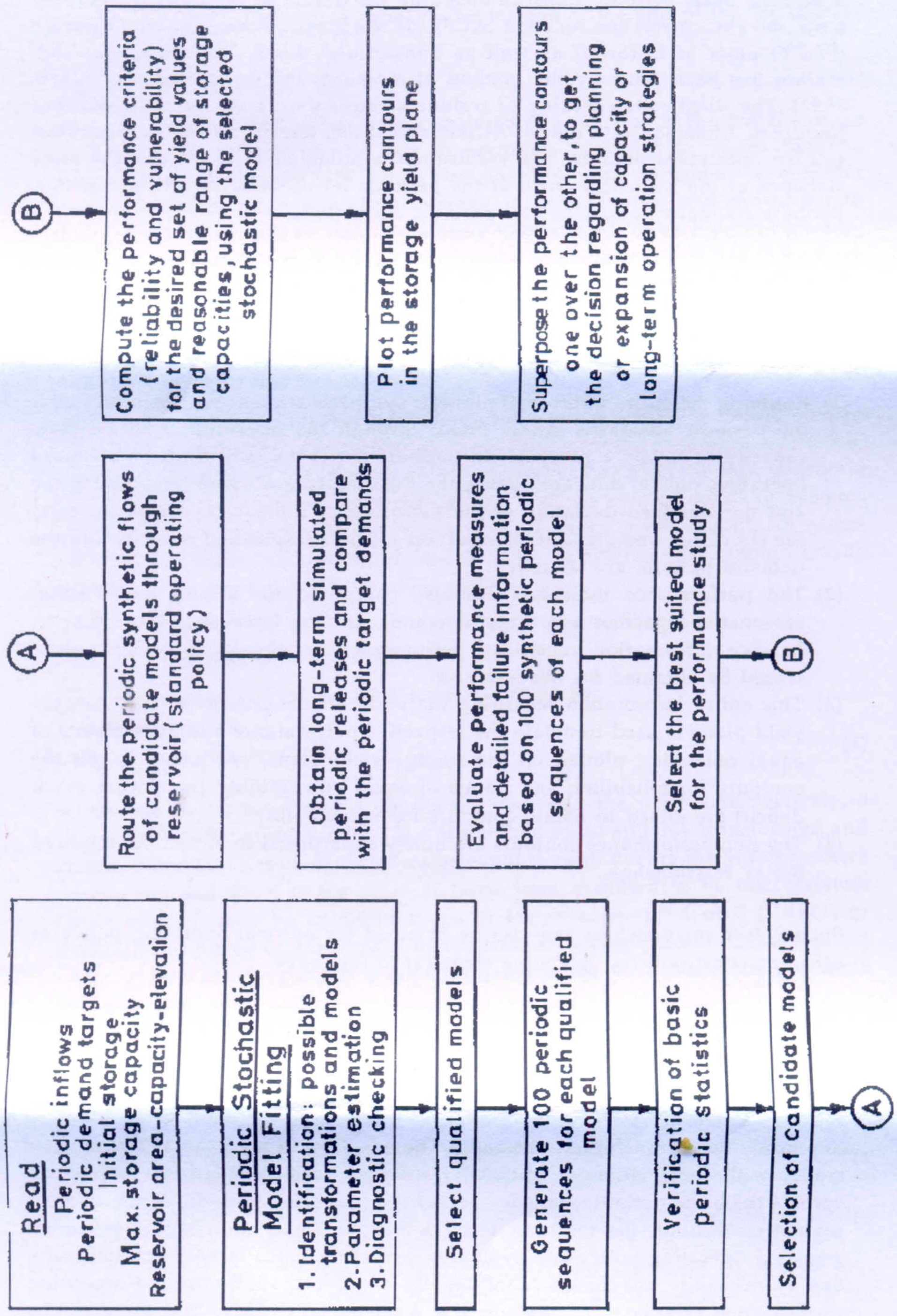
Read
Periodic inflows
Periodic demand targets
Initial storage
Max. storage capacity
Reservoir area-capacity-elevation
Periodic Stochastic Model Fitting
1. Identification: possible transformations and models
2. Parameter estimation
3. Diagnostic checking
Select qualified models
Generate 100 periodic sequences for each qualified model
Verification of basic periodic statistics
Selection of candidate models
A
A
Route the periodic synthetic flows of candidate models through reservoir (standard operating policy)
Obtain long-term simulated periodic releases and compare with the periodic target demands
Evaluate performance measures and detailed failure information based on 100 synthetic periodic sequences of each model
Select the best suited model for the performance study
B
B
Compute the performance criteria (reliability and vulnerability) for the desired set of yield values and reasonable range of storage capacities, using the selected stochastic model
Plot performance contours in the storage yield plane
Superpose the performance contours one over the other, to get the decision regarding planning or expansion of capacity or long-term operation strategies

Table 1. Salient features of Hemavathy Reservoir

Location	Upper reaches of Cauvery river basin in Southern India
Gross storage capacity	1048 M m^3
Live storage capacity	962.77 M m^3
Water spread area	8502 ha
Catchment area	5910 km^2
Command area	250 000 ha
Types of soil	Red loamy soil and red sandy soil
Average monthly temperature	18°C to 32°C
Crops grown	
Kharif (wet) season (Jun–Oct)	Rice, Jowar, Ragi, Maize, Groundnut, Tobacco, Potato, Soyabean
Rabi (dry) season (Nov–Mar)	Ragi, Jowar, Maize, Wheat, Groundnut, Potato, Coriander, Soyabean, Safflower, Pulses

Case Example: Hemavathy Reservoir

An existing reservoir, namely Hemavathy reservoir, located on the river Hemavathy, a tributary of the Cauvery river in the state of Karnataka, Southern India, is taken up to illustrate the construction of the performance relations on the storage–yield plane. The salient features of the reservoir are listed in Table 1. The river flows are south-west monsoon-dependent. The unregulated flows measured for a period of 58 years (1916–74) (Table 2) at a downstream gauging station have been used as inflows in this study. From Table 2, it may be observed that more than 88% of the annual flows occur in five continuous months, while the flows in the remaining months account for only about 12%, even though the demand targets are considerable in most months.

This means that the reservoir will fill during the monsoon period (June–October) and empty during December–March. Thus, within-year storages are predominant. The monthly irrigation requirements for various crop activities under the project command have been taken from the irrigation requirements computed by Srinivasan & Thandaveswara (1991). First, selection of the suitable periodic stochastic model for the performance study is discussed.

Inspection of the historical flow data and the identification based on the autocorrelation function (ACF) and the partial autocorrelation function (PACF) plots suggested that a periodic autoregressive model of order two (PAR(2)) would be suitable. The periodic statistics of the historical flows are presented in Figure 2. However, three low-order periodic models, namely PAR(1), PAR(2)

Table 2. Mean monthly flows and monthly target demands

Month	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
Mean monthly Flow (M m^3)	150	856	665	298	285	127	55	30	18	14	14	36	2548
Target demand (M m^3)	165	260	275	75	50	120	280	350	225	80	20	10	1910

and PARMA(1,1), were fitted in combination with Wilson–Hilferty transformation (WHT), logarithmic transformation (LOG) and periodic power transformation (POT). In the case of POT, all the modelling and generation steps had to be repeated many times to obtain the set of fine-tuned periodic exponents (Table 3), which reproduced the basic periodic statistics very well. For three months, namely February, March and April, no transformation was required, and hence the exponents for these three months in the case of POT are taken as 1.0. Since there is no zero flow in the entire historical flow data, the additive constants for all the months have been kept at 0.0 (Table 3). For all the models considered, after estimating the periodic parameters using method of moments, the diagnostic checking of residuals was carried out. It was found that only PAR(1)WHT, PAR(2)WHT and PAR(2)POT models passed all the diagnostic checks. PAR(2)LOG was a close contestant and, because of its versatility in monthly flow modelling, it was also included as one of the competing models to be considered for the reservoir performance study.

Second, the construction of the S–P–Y relationships is illustrated and their usefulness is discussed. In this regard, the performance criteria of the reservoir, namely mean reliability and mean vulnerability, are evaluated for a wide range of storage capacities (20% to 70% of mean annual flow [MAF] at 4% intervals) and demand target levels varying between 25% and 75% of MAF at 2% intervals, routeing the 100 periodic streamflow sequences generated from the selected stochastic model. Even though 1000 sequences may be ideal for the performance study, 100 sequences only are used for the purpose of demonstrating the construction of the S–P–Y relationships. The long-term monthly operation of the reservoir has been simulated using the standard operating policy already described. The contours of reliability and vulnerability are drawn on the storage–yield plane. The superposition of these contours one over the other gives the S–P–Y relationships for the Hemavathy reservoir under standard operating policy conditions. Thus, the problem is treated entirely as a planning problem, as if the reservoir were to be designed. Further, the usefulness of the S–P–Y relationships for reservoir capacity expansion problems is also discussed.

Results and Discussion

The results of the model verification are presented in Table 4 and Figure 2. It is observed from Table 4 that the relative root mean-square errors for the overall mean and standard deviation are least in the case of PAR(2)POT, followed by PAR(2)WHT and PAR(1)WHT. As far as the lag-one and lag-two periodic serial correlations are concerned, the models of order two perform reasonably well. Amongst the models listed in Table 4, PAR(2) with periodic transformation (POT) is selected for the reservoir performance study of the Hemavathy reservoir, based on the minimum relative root mean-square errors of overall mean, standard deviation and correlations. Since the model selected for this study is PAR(2)POT, the typical results and the discussion of the same are presented only for PAR(2)POT.

The contours of reliability drawn on the storage–yield plane are shown in Figure 3. The contour interval adopted is 0.05 in the range 0.65–0.95, 0.01 in the range 0.95–0.99, and 0.002 in the range 0.99–0.998. This set of contours provides information regarding the storage–reliability–yield relationships.

The contours of vulnerability are drawn in the range of 50–650 M m^3 on the

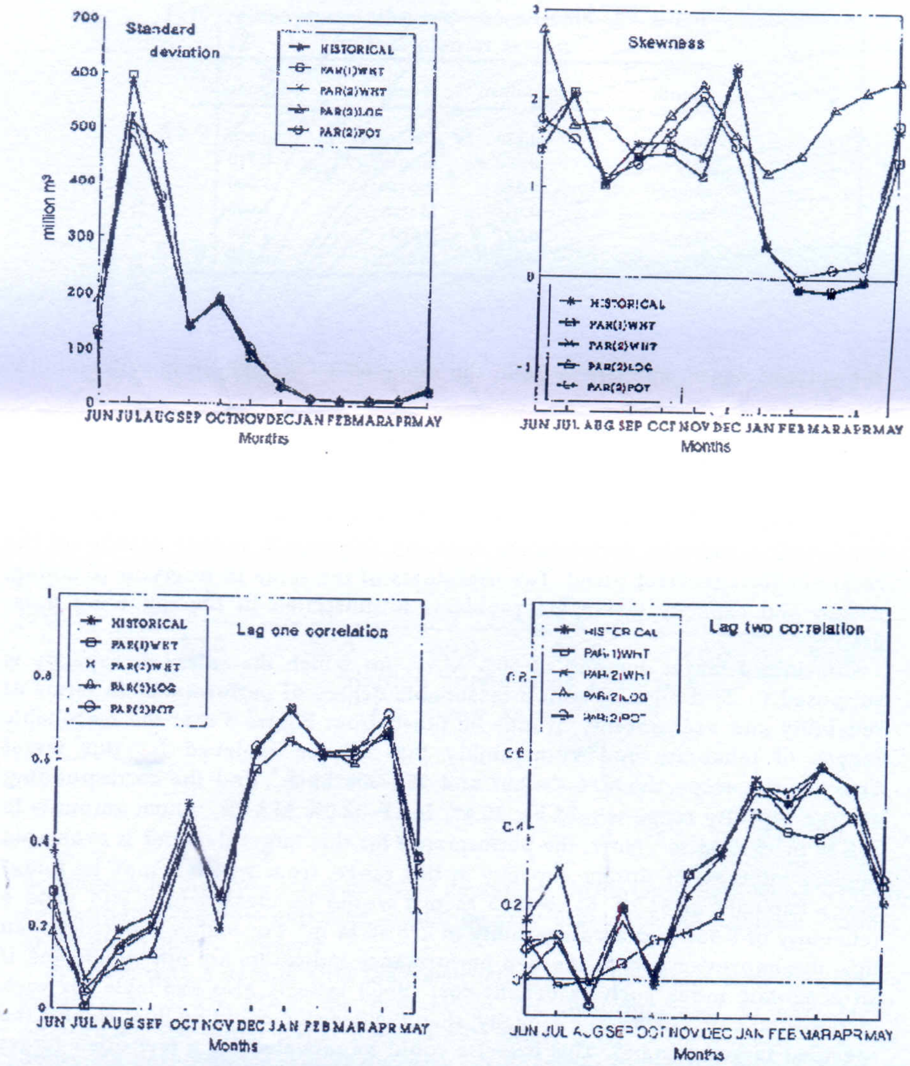

Figure 2. Preservation of basic periodic statistics.

storage–yield plane at an interval of 50 M m^3 (Figure 4). It is to be noted that the vulnerability refers to the maximum event deficit in this paper, and not the maximum single period deficit. The vulnerability contours clearly show the practical limits of demand targets which could be met for the given capacity of the reservoir system; and give an idea of the storage capacity required to meet a prescribed target demand with a reasonable vulnerability at the planning stage. From Figure 4, it may be seen that in case a high target requirement of, say, 75% MAF is set, even a high storage capacity of 60% MAF will give rise to a high vulnerability close to 500 M m^3. A practical range of demand target for

Table 3. Fine-tuned periodic exponents of power transformation

Month	Exponent	Month	Exponent
June	0.230	December	0.060
July	0.060	January	0.710
August	0.250	February	1.000
September	0.048	March	1.000
October	0.071	April	1.000
November	0.034	May	0.150

the system, hence, appears to be in the range 60–65% MAF, from vulnerability consideration.

Usefulness of S–P–Y Relationships

Figure 5 shows the S–P–Y relationships for the reservoir system, obtained by superposing the two performance contours (Figures 3 and 4) drawn on the common storage–yield plane. The usefulness of the same in reservoir planning, design and capacity expansion problems is illustrated in the following paragraphs.

Consider a target demand of 60% MAF, for which the reservoir capacity is supposed to be designed, with a reasonable degree of performance in terms of reliability and vulnerability. It may be noted from Figure 5 that the reasonable ranges of reliability and vulnerability that can be achieved for this target demand are, respectively, 0.95–0.97 and 250–300 M m^3, and the corresponding storage capacity range would be: 30.4% MAF–32.0% MAF%, which amounts to 775 M m^3–815 M m^3. Now, the performance for this target demand is evaluated at close intervals of storage capacity in this range, from which it may be found that a capacity of 31.2% MAF (795 M m^3) would be ideal, which will yield a reliability of 0.961 and a vulnerability of 278.50 M m^3. For higher capacities than this, the improvements in the two performance indicators are not significant. If an economic index such as benefit–cost (B–C) ratio is also available for each incremental value of storage capacity, then the decision could be finalized for the specified target demand. This exercise could be repeated for a few other target demands in the close range. Thus, the sensitivity of the storage capacity with regard to the target demand can be worked out using the S–P–Y relationships

Table 4. Relative root mean-square error of basic statistics.

Model	Mean	SD	Lag-one correlation	Lag-two correlation
PAR(1)WHT	0.153	0.384	0.290	—
PAR(2)WHT	0.152	0.369	0.289	0.408
PAR(2)LOG	0.155	0.499	0.343	0.532
PAR(2)POT	0.134	0.293	0.293	0.475

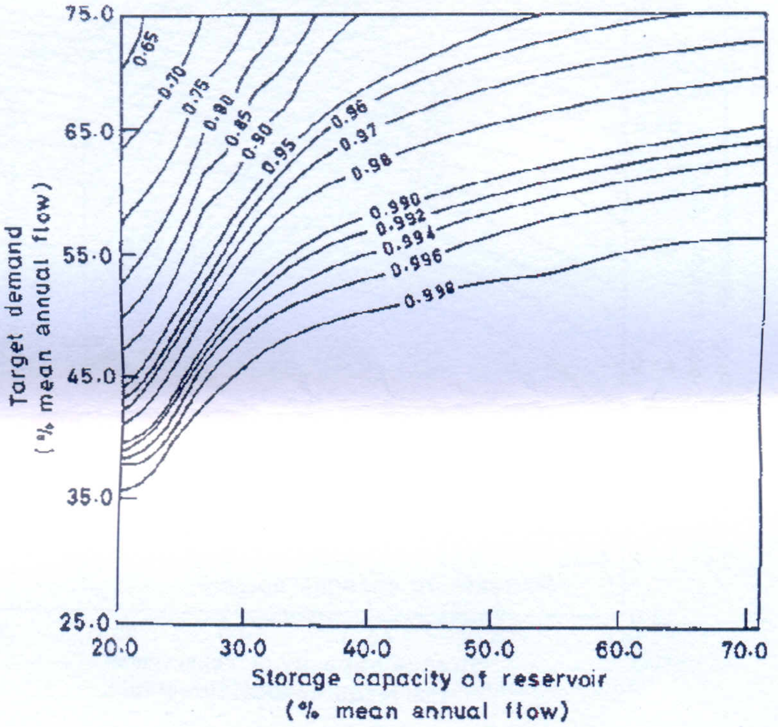

Figure 3. Contour for reliability.

developed, in the close range of target demands. This information, along with an appropriate economic indicator, would be very useful for the reservoir planner to fix the required capacity.

Suppose that, a decade after the construction of the reservoir with the storage capacity as 31.2% MAF, the demand in the field increases to 65% MAF, outgrowing the initial target fixed at 60% MAF. Now, if the expansion is not done, the performance would decrease considerably (reliability would drop to 0.903 and vulnerability would increase to 410 M m^3). On the other hand, if the performance is to be maintained at a reasonable level, then capacity expansion is to be undertaken. Storage capacity ranging from 32% to 35% MAF may be tried out, which would yield a reasonable range of reliability and vulnerability (Figure 5). The performance indicators are computed for this range of storage capacities at close intervals and it is found that 33.4% MAF (851 M m^3) would be an ideal choice, which yields a reliability of 0.940 and a vulnerability of 397 M m^3. However, the economies of scale concerning the capacity expansion and the increased benefits that would accrue from the increased demand have to be considered along with the reservoir performance indicators, while arriving at a decision regarding the capacity expansion.

It is to be noted that, owing to lack of space, the performance contours shown in Figure 5 are drawn at coarse intervals. However, if performance contours are

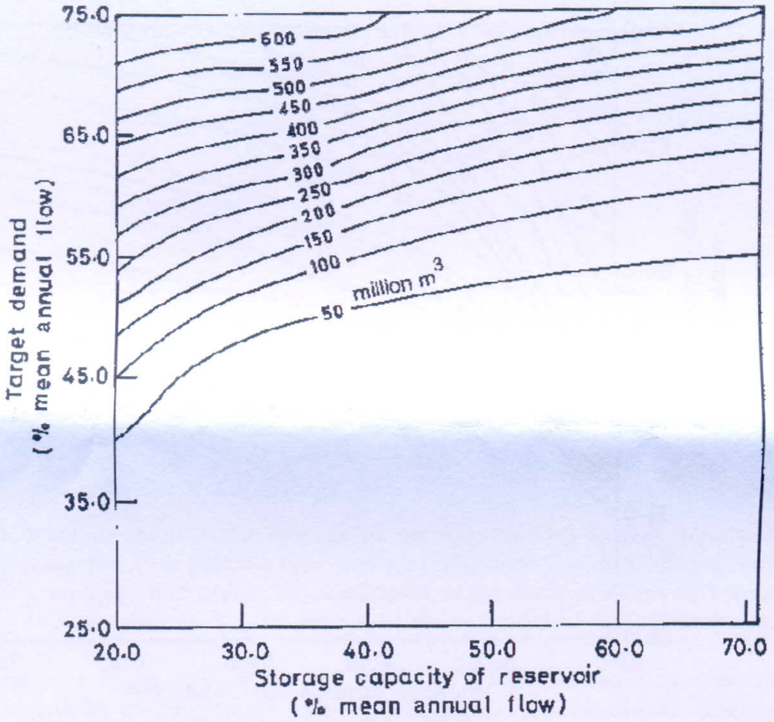

Figure 4. Contour for vulnerability.

required at finer intervals, the same may be drawn on a bigger size sheet for the purpose of clarity, using closer intervals of storage capacity and target demand. In short, the superposed S–P–Y relationships mimic the task of a stochastic hydrologist and could serve as a ready reckoner for the decision maker in planning, design and capacity expansion problems.

Only two performance indicators have been used in this study. It is possible to consider the other indicators such as resilience, average deficit, period vulnerability, and draw similar contours for each indicator. But, if more than two indicators are used, then a decision-aid is to be built in to select the storage capacity for a set of desired indicators. Of course, the selection of the set of performance indicators, their prioritization and the specification of the desired ranges depend on the purpose of water use and the system itself.

Conclusions

In this paper, storage–performance–yield (S–P–Y) relationships are developed for a single reservoir by stochastic simulation using standard operating policy. Contours of reservoir performance, namely reliability and vulnerability, have been drawn on the storage–yield plane, the superposition of which result in the S–P–Y relationships for the reservoir system. These S–P–Y relationships will be useful for making planning decisions regarding reservoir capacity and will also

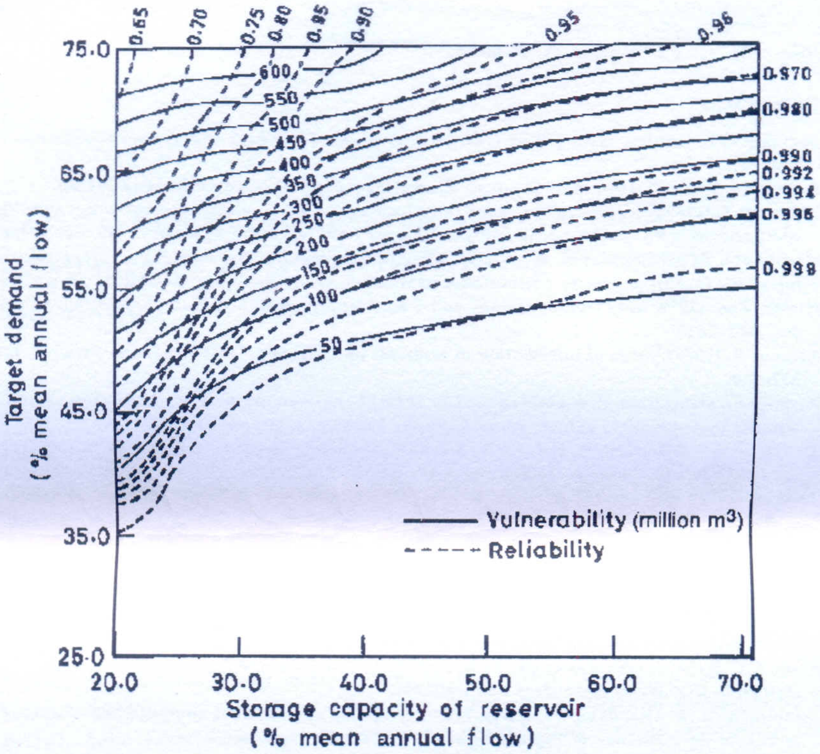

Figure 5. Superposition of performance contours.

aid in reservoir capacity expansion problems and in deriving modifications to long-term operational strategy for existing reservoirs, to yield the desirable performance. The construction of the S–P–Y relationships and their usefulness have been illustrated through a real case example of an existing irrigation reservoir located in the state of Karnataka in Southern India. For any given reservoir system, the S–P–Y relationships can be constructed for different operating policies following the steps indicated in Figure 1. However, it should be mentioned that the planning and operating decisions would be more meaningful only when they are supported by rigorous economic analysis.

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