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RELIABILITY OF CYCLIC SURFACE AND GROUNDWATER STORAGE SYSTEMS FOR WATER SUPPLY: A PRELIMINARY ASSESSMENT

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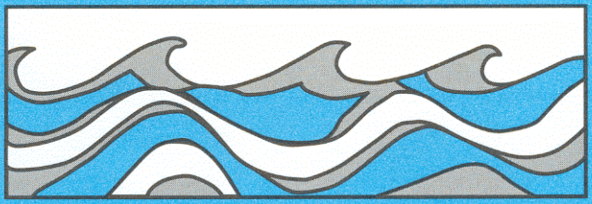

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by

Dennis P. Lettenmaier and Stephen J. Burges

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Abstract

The performance of a simplified water resource system consisting of a single surface reservoir and adjacent aquifer storage operated as a coupled flow buffering device was investigated to provide insight into the most important physical and climatic (streamflow) parameters governing cyclic storage performance. The simplified system was driven by stochastically generated annual inflows to the surface reservoir. The surface reservoir was operated to meet a fixed annual demand; if the demand could not be met the deficit was made up if possible by groundwater pumpage subject to constraints on aquifer storage and pumping capacity. Excess reservoir release was used to recharge the aquifer subject to the aquifer storage capacity and maximum annual recharge capacity. The system is fully characterized by the aquifer capacity, pumping and recharge capacity, surface storage size, annual demand, and reservoir inflow statistics, including mean, coefficient of variation, skew coefficient, lag one correlation coefficient, and Hurst coefficient.

The system operation was summarized by the empirical cumulative distribution function of 18 performance measures taken over 500 synthetically generated inflow sequences for each of 32 physical and streamflow parameter combinations. The most informative performance measures were found to be the number of periods (years) of record during which 100 and 80 per cent, respectively, of the nominal demand was statisfied, and the number of periods in which pumping was (a) required, (b) exceeded 50 per cent of capacity, and (c) equalled capacity. In the cases investigated, annual pumping capacity was always set at 0.4 times the mean annual reservoir inflow, with annual recharge capacity an intentionally large 1.0 times the mean annual reservoir inflow. Under these conditions, system performance was almost always limited by total system storage, i.e., surface and aquifer storage. The effect of streamflow persistence and variability and skewness of streamflows on system reliability was much as has been observed elsewhere for surface storage along; specifically, increasing long term persistence markedly reduces reliability, and variability and skewness of the marginal distribution have a somewhat less pronounced effect in degrading reliability.

A preliminary economic analysis was conducted for a range of systems with fixed streamflow parameters and aquifer size, and a range of surface storage pumping capacity combinations selected to result in the same system reliability. Two measures of reliability were considered; with both measures the least cost system was that with the minimum surface storage sufficient to allow the system to meet the reliability requirement. Generally, it was found that the cost of providing buffering against variations in streamflow was about an order of magnitude less by developing aquifer storage as compared to providing surface storage. Although this result is subject to a number of simplifying assumptions which suggest it may represent an upper bound, the economic implications should be sufficient to encourage further, more detailed, analyses.

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Chapter 1

INTRODUCTION

As the best available sites for surface storage facilities have been used and environmental considerations have eliminated some remaining potential sites, water resource managers have looked to alternative means for providing new sources of water supply and making better use of existing facilities. Although both ground and surface water sources are widely used for water supply, these sources are most often considered as independent storage reservoirs. Numerous examples of unsatisfactory performance of systems relying on single sources may be found in the Western United States. In the Southwest, especially where rapid demographic changes have occurred, there has been a tendency, prompted by the relatively low capital expenditures required, to exploit groundwater systems. In a number of cases, the result has been overdrafting of groundwater supplies, or mining of groundwater. Physical constraints on the extend of the aquifers involved as well as water quality considerations indicate that mining cannot continue indefinitely, and costly alternatives ultimately will become necessary. Two particular examples are the Las Vegas and Tucson areas. Both communities have looked to costly diversion of Colorado River water (itself a limited resource) as the solution to the overdrafting problem.

In contrast to the rather long-term failure modes encountered in excessive reliance on groundwater supplies, shorter scale (e.g., annual or seasonal) failures may result from exclusive use of surface supplies. The difference in time sclaes results because typical surface storage reservoir volumes are much smaller compared to abstractions than are groundwater supplies. Examples of the inability of surface supply systems to provide their target supply levels abound in the 1976-77 Western drought, particularly in California.

Despite such disadvantages of reliance on a single-source supply, effective joint use of surface and groundwater sources is a research area which has been largely neglected. For instance, although early in the development of the Central Valley Project and the California State Water Project, joint, or conjunctive use of ground and surface water was proposed, the groundwater management aspects were, in large part, ultimately ignored (Thomas, 1978) and groundwater has come to be viewed as a backup source, rather than being integrated into a comprehensive system development plan. Likewise, in situations where conjunctive use has been employed, the groundwater resource has often not been viewed as a potential natural storage facility, which might complement surface storage. Groundwater resource management has instead largely emphasized the concept of sustained yield, wherein long-term extraction rates are presumed to be limited by natural recharge. Except in a few specialized cases, the concept of extensive artificial recharge, especially during years or seasons of excess surface runoff, has received little attention. It is this concept which has the potential to place groundwater storage in the position of complementing surface storage in an integrated management system.

BACKGROUND

Although the concept of cyclic storage was recognized almost 30 years ago by Banks (1953) and co-workers on the California Water Plan (California Department of Water Resources, 1957; 1975) this approach to joint design and operation of ground and surface water supplies has never been implemented on a regional scale. Notable examples of use of cyclic storage on a smaller scale exist in several California coastal areas where subsurface storage has been used to buffer variability in surface supplies through artificial recharge of excess surface water (in some cases, treated wastewater) when available. A large stumbling block for practical implementation of cyclic storage has been the manner in which costs of surface storage facilities are allocated, and legal problems in control of subsurface storage (Thomas, 1978; Gleason, 1976; 1978).

The research community has given little attention to the problem of cyclic storage in favor of the conjunctive use issue. Although the division between these topics is not always clear, we consider here that cyclic storage refers to long-term management of surface and subsurface storage to improve system operating performance (e.g., resistance to droughts). Conjunctive use, on the other hand, is taken to refer to the mechanics of stream-aquifer interactions, and related management options which exploit synergisms between surface flow and groundwater gradients for such objectives as operation of a surface reservoir at minimum cost. Burges and Maknoon (1975) reviewed 15 conjunctive use studies and found that the objective of most of these studies was to meet water demand and instream flow requirements while minimizing variations in piezometric head. In these studies, subsurface storage was not generally viewed as a potential alternate flow buffer to surface impoundments. Also, the time scale of conjunctive use investigations is usually much shorter than that of interest in cyclic storage.

The concept which we explore in this report is the joint operation of a hypothetical single surface reservoir and adjacent aquifer storage as coupled flow buffering devices. In the hypothetical system modeled, the surface reservoir was operated to provide maximum smoothing of annual outflows to minimize negative deviations from the imposed (constant) demand. Aquifer storage was operated as a secondary reservoir to make up deficiencies in outflow from the surface reservoir. Aquifer recharge was provided by excess surface releases in periods of above normal reservoir inflow. Withdrawals from and recharge to the aquifer were limited by its finite extent. Stochasticity of reservoir inflow was represented by examining statistics describing performance of the system over a number of synthetically generated streamflow sequences.

The aim of the study was to determine the potential applicability of cyclic storage in the framework described over a range of reservoir inflow, surface storage, demand, and aquifer characteristics. As such no given physical system was modeled; instead parameter ranges were investigated which encompass a number of particular physical systems. It is emphasized that this study is preliminary and was designed to identify situations where more detailed study is advisable. Complete details of the system model used are given in Chapter 2.

Two criteria for assessment of system performance were used here: physical and economic. Physical performance was measured by several indices of aggregate system supply deficits, pumping requirements, and frequency of occurrence of physical system limitations (e.g., empty and full aquifer and surface storage; pumping or recharge equal to capacity). Economic performance was measured as the discounted total system cost over an assumed 40 year project life, aggregated according to surface reservoir capital and OMR costs, and capital cost of pumping and associated equipment, discounted OMR, and energy costs. These economic criteria were reviewed for several surface and aquifer storage combinations having the same physical supply performance.

OBJECTIVES

The objectives of the work reported herein were:

1) To develop an annual scale operating model of a jointly operated surface storage reservoir and adjacent aquifer storage capable of reflecting the stochastic nature of reservoir inflow. The model was appropriately

simplified to allow screening of a large number of hypothetical physical and demand characteristics.

2) To estimate ranges of parameters describing surface reservoir inflow, surface reservoir and aquifer sizes, system demand, and aquifer pumping and recharge capacities for which cyclic storage appears feasible. Of particular interest here were physical limitations which might restrict applicability of the concept.

3) For a smaller subset of the parameters investigated in 2), to estimate the relative economic cost of alternate combinations of surface and aquifer storage having the same physical supply performance characteristics.

The results of work performed here directed at each of these objectives are presented in Chapters 2, 3, and 4, respectively. The study is summarized in Chapter 5, along with a review of the basis for the model used and considerations for implementation of cyclic storage not directly incorporated in the model.

CHAPTER 2

MODEL DEVELOPMENT

A simulation approach was used to examine the surface and aquifer storage interactions of interest. Since the principle objective of the research was to identify physical parameter ranges over which a cyclic storage alternative appears feasible, a large number of simulations were required. This restricts model complexity to a level which allows any given simulation, i.e., record of simulated system performance over a specified project life, to be obtained quite inexpensively. Simulation cost is especially critical since many system performance variables are stochastic; the only viable method of estimating the characteristics of most of these variables is by Monte Carlo sampling. Hence, for any given combination of physical parameters, many simulations must be performed; to extend the analysis over a sampling field in multivariate physical parameter space necessitates a great deal of computation.

These considerations lead us to model the simplest physical system which includes characteristics considered essential to allow generalization of results. As such, the prototype system was taken to consist of a single surface reservoir which releases water for irrigation purposes to an area underlain by a substantial aquifer. The aquifer may be pumped up to a maximum rate by wells spaced throughout the area. Water released from the reservoir and diverted to the irrigation area is supplemented by water pumped from the aquifer to attempt to satisfy a specified physical demand for water. The combined surface and aquifer storage system is operated to satisfy as much demand as possible from surface reservoir releases; pumped water is used to satisfy as much of any shortfall as possible subject to constraints on pumping and the physical size of the aquifer. Excess reservoir releases, when available, are used to recharge the aquifer up to given physical constraints on recharge capacity and aquifer size. A range of physical parameters including reservoir and aquifer sizes, pumping and recharge capacities, and streamflow conditions were examined to determine long-term storage fluctuations and the ability of the combined system to meet sustained demands.

In all cases an annual time scale was used; to be of practical interest this roughly requires total storage capacity (surface and aquifer) to exceed mean annual surface streamflow. As such, some of the combinations used may be impractical in specific situations where a time scale reflecting seasonality in streamflow and irrigation demand is appropriate. Likewise, even where examination of annual totals is sufficient, seasonal constraints on certain processes such as pumping and recharge may require consideration of a seasonal time scale. For the present, exploratory purposes, however, an annual time scale was favored because it permits examination of general system interactions over a much wider range of physical parameters than would otherwise be possible.

SYSTEM MODEL

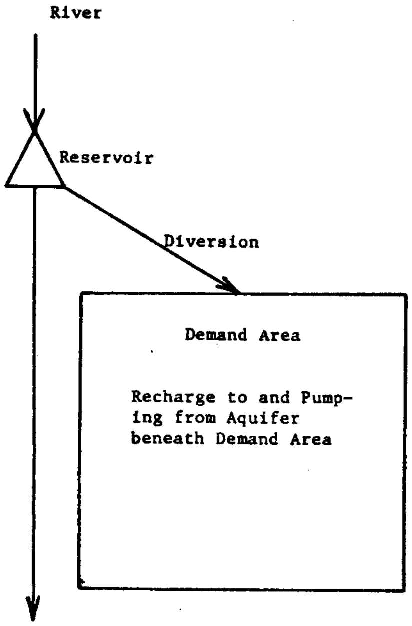


Figure 2.1 System Schematic

The basic geometry modeled is shown in Fig. 2.1. We assume that a surface reservoir site exists on the stream and that all water use is downstream from the reservoir site. A diversion canal delivers the controlled release from the reservoir to the irrigated area. The same distribution system is used regardless of whether water is supplied from the reservoir or from wells. Stream-aquifer interactions are not considered.

Releases from the reservoir are on a maximum ignorance basis; no forecasting of future inflow to the reservoir is made. This is sensible because of the annual time scale used. Reservoir release follows the simple scheme illustrated in Fiering (1967) and shown in Fig. 2. This operating schedule does not have any mechanism of valuing future releases. If available water is less than the target release (specified physical demand) then all water is released. When available water exceeds the target, the target quantity is released and excess water is stored up to the reservoir full state. If more water is available it is spilled. Spilled water, or water beyond the reservoir capacity, is available to recharge the aquifer. The system

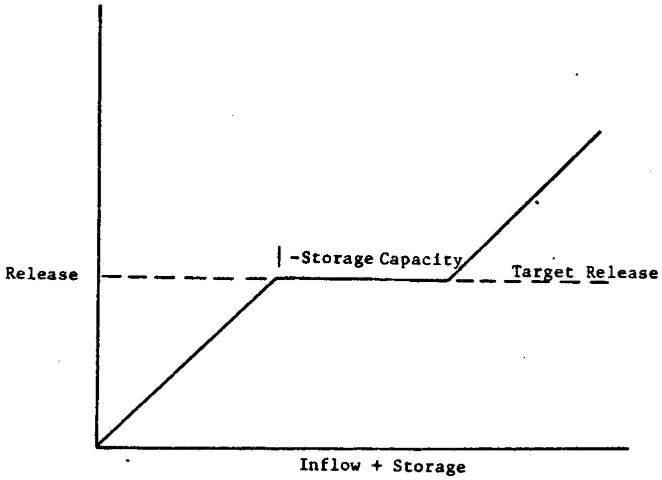


Figure 2.2 Surface Reservoir Release Policy

model is described mathematically as follows: The reservoir has inflow Q_t in year t, size S_{max}, and storage content S_t at the beginning of year t. Controlled release X_t has an upper limit set by the total physical demand D_t. Uncontrolled release (spill) is E_t. The aquifer has capacity C_{max} and C_t is the amount of water in the aquifer at the beginning of time period t. The maximum pumping rate from the aquifer in any year is P_{max}; the actual rate is P_t. The maximum aquifer controlled recharge is I_{max}, the rate in year t is I_t. All of these quantities are fractions of the mean annual streamflow into the reservoir. The initial aquifer and storage reservoir contents are specified and the system operated for a particular streamflow statistical population for a period of T years. The water supplied in year t is Y_t. Thus, system operation is formulated as follows:

Reservoir Mass Balance and Operation:

$$S_{t+1} = S_t + Q_t - X_t \tag{1}$$

$$\left.\begin{aligned} X_t &= Q_t + S_t \\ E_t &= 0 \end{aligned}\right\} \quad S_t + Q_t \leq D_t \tag{2}$$

$$\left.\begin{aligned} X_t &= D_t \\ E_t &= 0 \end{aligned}\right\} \quad S_t + Q_t - D_t \leq S_{max} \tag{3}$$

$$\left.\begin{aligned} X_t &= D_t \\ E_t &= S_t + Q_t - D_t - S_{max} \end{aligned}\right\} \quad S_t + Q_t - D_t > S_{max} \tag{4}$$

$$S_{t+1} = S_{max}$$

Aquifer Operation:

$$C_{t+1} = C_t + I_t - P_t \tag{5}$$

$$P_t = 0 \quad ; \quad X_t = D_t \tag{6}$$

$$P_t = D_t - X_t \leq P_{max}; \quad X_t \leq D_t \tag{7}$$

$$I_t = 0 \quad ; \quad E_t = 0 \text{ or } C_t = C_{max} \tag{8}$$

$$I_t = E_t \leq I_{max} \quad ; \quad C_t \leq C_{max} \tag{9}$$

Supply:

$$Y_t = X_t + P_t \tag{10}$$

Each variable having subscript t is an element of a vector representing multiple realizations of that quantity. The Monte Carlo analysis consisted of computing performance measures for each vector for streamflow sequences of length T years.

STREAMFLOW MODEL

An ARMA-Markov model (Lettenmaier and Burges, 1977) was used to generate streamflow sequences having different amounts of persistence. This model permitted analysis of the effects of flow scenarios reflecting long, sever droughts as well as shorter-term droughts. Streamflow parameters were varied to reflect scenarios ranging from high frequency, lag-one Markov (Matalas, 1967) to long-term persistence (Hurst, 1951; Hurst et al., 1965). An additional feature of the flow model is its ability to model streamflow volumes that follow a three parameter log normal (LN3) probability distribution. Details of this distribution are given in Burges, et al. (1975).

The standard Arma-Markov process (having zero mean and unit variance) is

$$Z_t = V_t + W_t \tag{11}$$

$$V_t = \rho_M V_{t-1} + \varepsilon_t \tag{12}$$

$$W_t = \phi W_{t-1} - \theta \eta_{t-1} + \eta_t \tag{13}$$

where Z_t is the ARMA-Markov process, eqn. (12) defines the Markov component, and eqn. (13) defines the ARMA (1,1) (Box and Jenkins, 1970) process. ε_t and η_t are normal random deviates having zero mean and variances $C_1(1-\rho_M^2)$ and $C_2[(1-\phi^2)/(1+\theta^2-2\phi\theta)]$ respectively. The model is defined by:

$$C_1 + C_2 = 1 \tag{14}$$

$$\rho(1) = C_1\rho_M + C_2\rho_{AM} \tag{15}$$

$$\rho_f(K_1,H) = C_1\rho_M{}^{K_1} + C_2\rho_{AM}\phi^{(K_1-1)} \tag{16}$$

$$\rho_f(K_2,H) = C_1\rho_M{}^{K_2} + C_2\rho_{AM}\phi^{(K_2-1)} \tag{17}$$

$$\rho_f(K_3,H) = C_1\rho_M{}^{K_3} + C_2\rho_{AM}\phi^{(K_3-1)} \tag{18}$$

where C_1, C_2, ρ_M, ρ_{AM}, and ϕ are all constrained to lie between zero and one. Simultaneous solution of eqns. 14-18 yields the model parameters. The desired lag-one correlation coefficient is $\rho(1)$, H is the Hurst coefficient to be preserved (= 0.5 for high frequence model, > 0.5 when low frequency Hurst effect is desired), and $\rho_f(K,H)$ is the correlation of Fractional Gaussian Noise (FGN), having Hurst coefficient H, at lag K. K_1, K_2 and K_3 are arbitrarily chosen to fit the FGN correlation structure with the combined ARMA-Markov structure. Typical values of K_1, K_2 and K_3 are T/8, T/2 and T.

For a process that is normally distributed and with mean $\overline{Q}$ and standard deviation σ_Q, eqn. (11) is scaled to yield:

$$Q_t = \overline{Q} + \sigma_Q Z_t \tag{19}$$

For flows that are LN3 distributed with mean $\overline{Q}$, standard deviation σ_Q, and skew coefficient G_Q, model parameters μ, σ and a, for use in a normally distributed domain are (Burges, et al., 1975):

$$\overline{Q} = a + \exp\,(\mu + \frac{\sigma^2}{2}) \tag{20}$$

$$\sigma_Q^2 = (\exp(\sigma^2) - 1)\ \exp(\sigma^2 + 2\mu) \tag{21}$$

$$G_Q = \frac{\exp(3\sigma^2) - 3\ \exp(\sigma^2) + 2}{(\exp(\sigma^2) - 1)^{3/2}} \tag{22}$$

Desired synthetic flow sequences are generated by scaling eqn. (11):

$$U_t = \mu + \sigma Z_t \tag{23}$$

$$Q_t = a + \exp\,(U_t) \tag{24}$$

Details for obtaining ARMA-Markov parameters for skewed flow situations are given in Lettenmaier and Burges (1977). Usually if H and $\rho(1)$ are to be preserved, eqns. (14)-(18) are solved using values of H and $\rho(1)$ (which are operative in a logarithmic domain) that are slightly larger than the values in the untransformed domain. This increase is usually on the order of one per cent.

SYSTEM PERFORMANCE MEASURES

The system operating model was coded in FORTRAN IV. Since the nature of the study was exploratory, it was initially desired to make use of as many summary performance measures (e.g., summary statistics and physical response characteristics) as possible. The strategy taken was to select performance measures such that a single index would characterize some aspect of the system for a given reservoir inflow scenario. The summary performance measures used are identified in Table 2.1. Subsequently, the most informative measures were identified, and their cumulative probability distributions estimated. A preliminary review of the results indicated that the supply (number of periods demand fully satisfied; number of periods more than 80 per cent demand satisfied) and pumping (number of periods pumping required; number of periods pumping exceeds 75 per cent capacity; number of periods pumping equals capacity) indices given in Table 2.1 were retained for each of the runs discussed in Chapter 3, and are available from the authors on request.

Table 2.1 Summary Information for Cyclic Storage Operation

- Number of periods demand fully satisfied
- Number of periods more than 80% demand supplied
- Number of periods corresponding to maximum cumulative supply shortfall
- Period when maximum cumulative supply shortfall ends
- Maximum cumulative supply shortfall
- Number of periods when reservoir storage is less than initial storage
- Number of periods when reservoir is empty
- Maximum number of consecutive time periods reservoir is empty
- Maximum consecutive time periods reservoir is not full
- Maximum consecutive time periods reservoir storage is less than initial storage
- Minimum aquifer storage
- Maximum number of consecutive periods aquifer storage is less than 50% initial
- Number of periods pumping required
- Number of periods pumping exceeds 50% of capacity
- Number of periods pumping equals pumping capacity
- Number of periods recharge effected
- Number of periods recharge exceeds 50% of capacity
- Number of periods recharge equals capacity

Chapter 3

MODEL IMPLEMENTATION

In Chapter 2 we defined the mathematical representation of a hypothetical surface reservoir and groundwater aquifer to be used to attempt to meet a physical demand for water. To determine what size combinations have significance when cyclic storage use is being considered, it is necessary to explore appropriate combinations of physical parameters describing streamflow, pumping and recharge rates, and storage capacities. For our simplified system, apart from streamflow descriptors, there are five major parameters (surface reservoir size, S_{max}; Aquifer storage capacity, C_{max}; Demand, D_t; Maximum Pumping Rate, P_{max}; and Maximum Recharge rate, I_{max}) and two initial conditions (initial contents of the surface reservoir and the aquifer, S_o and C_o, respectively) which must be considered. This clearly leads to an impossible combinatorial parobolem if each parameter is discretized and all possible combinations are examined. In an operational situation, of course, some of these parameters are fixed; however, to maintain the general applicability of the study we consider all as variables here. Clearly, judicious selection of parameter combinations is essential.

Our primary interest was in long-term cyclic drafting of water from reservoir and aquifer storages so the effects of initial transients were not studied. We assumed that the aquifer was full at the beginning of an operating cycle and that the surface reservoir was 20 per cent full at the time it was brought into service. Similarly, a constant physical demand, $D_t = D$, $0 < t \leq T$ was used. It is recognized that demand patterns frequently change with time. However, Burges and Linsley (1971) have shown that reservoir storage requirements under time-changing demands can be represented by an equivalent constant demand. The sequent peak algorithm, used to determine required reservoir storage size in the Burges and Linsley work, and the simple operating rule for a fixed reservoir used here are closely related, consequently consideration of a constant demand scenario only was felt to be justified.

Based on previous work (e.g., Burges and Lettenmaier, 1977) we selected a project operating period of 40 years for our evaluations. Time horizons of this order are often justified for project evaluation on economic grounds, since benefits and costs over longer time horizons, when discounted at rates in the range commonly used have insignificant effect on benefit/cost ratios. However, physical considerations such as sedimentation of surface reservoirs, expected equipment operating life, etc. often point to similar project evaluation horizons.

Under these restrictions we were faced with a problem of investigating the effect of four parameters in addition to an array of streamflow populations. The model was implemented using several levels of each of these parameters as described below.

PARAMETER SELECTION

Streamflow Parameters

Four different streamflow populations were used. All were modeled using the ARMA-Markov model developed by Lettenmaier and Burges (1977). This model has the capability of representing scenarios displaying the Hurst effect (see Burges and Lettenmaier (1975) for a description of the Hurst effect and its consequences). Considerable dispute remains as to the existence or lack thereof of the Hurst effect in streamflow records. It is generally agreed, however, that if such an effect exists, it might result from either long-term memory of the generating process (the commonly used lag one Markov models have structure such that memory exists only between adjacent time periods; long-term persistence processes have memory for much longer periods) or from shifts in the mean of the generating process (Klemes, 1974; Potter, 1978). Regardless of the basis, the result of the Hurst effect is that much more lengthy droughts and long periods of excesses are possible, consequently larger storage is required to provide the same system reliability as compared with short memory (e.g., lag-one Markov) processes. The parameter used to index the Hurst phenomenon is the Hurst coefficient, H, which ranges from 0.5 (short memory) to 1.0 (long memory). Also of interest is the lag-one correlation coefficient, which determines the short-term behavior of the process, and which for the special case H = 0.5 is the sole persistence parameter of the ARMA-Markov model. The ARMA-Markov model is also capable of modeling skewed marginal streamflow distributions through use of the three parameter log normal (LN3) probability density function, which is generated by an exponential transformation of a translated normal variate (Burges, et al., 1975).

The four streamflow populations used are summarized in Table 3.1;

Table 3.1

Streamflow Populations

Case	H	$\rho(1)$	Coefficient of Variation CV	Skew Coefficient	Probability Distribution
1	0.8	0.4	0.5	1.0	LN3
2	0.7	0.2	0.5	1.0	LN3
3	0.5	0.2	0.5	1.0	LN3
4	0.5	0.2	0.25	0.0	Normal

in all cases the mean flow was taken as unity. Three of these populations represent relatively large annual variability and skewness, two of these represent substantial persistence effects as well. The fourth case represents a more benign regime both in terms of long-term persistence and variability and skewness of the marginal distribution which is not uncommon for streams flowing from the Cascade Mountains of the Northwestern United States.

Case 1 streamflows are the most persistent (short- and long-term) and have the same variability and skewness as cases 2 and 3. The Hurst coefficient used in this case, H = .8, reflects a high degree of long term persistence, and the lag one correlation $\rho(1) = 0.4$ represents substantial short-term memory as well. Case 2 (H = .7) was selected because it represents a regime which is close to the average found by Hurst in his studies of long term persistence (Hurst, et al., 1965). It should be noted that the levels of H used here are population values, whereas Hurst's work summarized sample estimates, which generally are biased upward. Consequently, it is likely that a population value of H = .7 represents scenarios which have greater long-term persistence than a population "average" (if such a concept is relevant) would reflect. The third streamflow case does not exhibit long-term persistence but retains the substantial variability and skewness of cases 1 and 2. The fourth case also belongs to the short-term persistence (Markov) domain; sequences generated from this population are much less variable than those generated for the first three populations. Previous work (Burges and Lettenmaier, 1977) has shown the relative significance of persistence. Flow variability, and skewness for different demand levels to be supplied from a single reservoir. The four cases selected here encompass streamflow model parameter ranges which bracket a region of parameter space containing most natural streams.

Physical System Parameters

The reservoir capacity, S_{max}, took values of one-half and twice the mean annual streamflow. An annual model is inappropriate if surface storage is much less than the former value, while the latter is near the practical upper limit usually imposed by site and evaporation considerations. There are few reservoirs of operational significance having storage larger than twice the virgin average annual flow. The aquifer capacity took on values of one and three times the mean annual streamflow volume. This range is based on physical considerations and on rough feasibility estimates for minimum aquifer storage.

The remaining system variables are maximum recharge rate, I_{max}, and maximum pumping rate. In this work we did not want the system to be limited by recharge capacity, so the maximum recharge rate was set equal to the mean annual streamflow volume. In most cases such a high recharge rate would not be physically reasonable, however, it does insure that recharge capacity will not limit system performance, which allows attention to be focused on surface/aquifer storage and pumping relationships. Further, a review of the simulation results indicated that for most configurations considered, the maximum recharge capacity was infrequently required. Only for demand 80% of the mean annual flow and for $S_{max} = 0.5$ was recharge effected at the maximum rate. Typically this rate was used in only one year of the operating life and occurred in fewer than 3% of flow sequences used.

The maximum pumping rate was set arbitrarily at 40% of the mean annual streamflow. This level was chosen to give a balance between the amount of water that could be supplied from the surface reservoir and the groundwater aquifer. The effect of pumping capacity on system performance is examined in connection with the economic analysis described in Chapter 4.

Two demand levels, 50 and 80% of the mean annual flow were used. These levels were used to bracket the cases which were considered to be of importance to cyclic storage. It is anticipated that future demand levels in the range 50 to 80% of mean annual flow will be experienced in many highly developed basins (National Water Commission, 1973). Higher demand levels require unrealistically large storage capacity to provide acceptable reliability, while lesser demand levels are more appropriately addressed through conjunctive use policies (see Maknoon and Burges, 1978).

The four system capacity combinations used are summarized in Table 3.2.

Table 3.2

System Capacity - Demand Combinations

S_{max}	C_{max}	I_{max}	P_{max}
0.5	1.0	1.0	0.4
2.0	1.0	1.0	0.4
0.5	3.0	1.0	0.4
2.0	3.0	1.0	0.4

Notes:
1) All quantities have been divided by the mean annual streamflow volume.
2) Demands used $D = 0.5, 0.8$.
3) Initial reservoir storage $S_o = 0.2S_{max}$.
4) Initial aquifer content $C_o = C_{max}$.

Each configuration was examined for two demand levels and four streamflow populations, so a total of 32 systems were reviewed.

Experimental Design

For a specific set of S_{max}, C_{max}, D, and a particular stochastic streamflow population, annual streamflow sequences of length T = 40 years were generated and routed through the cyclic storage system. Five principal performance measures were used: the number of years that demand was satisfied fully; the number of years that 80% of demand was satisfied; the number of periods that pumping was required; the number of years that pumping exceeded 0.5 P_{max}; and the number of years that pumping equaled P_{max}. These were stored for primary analysis. Each performance measure was summarized as the empirical cumulative distribution function of the measure resulting from 500 simulations. Fourteen additional secondary performance measures (see Table 2.1) were also computed.

Summarization of System Performance

For each streamflow-system size combination two cumulative probability diagrams were used to summarize supply and pumping features. Figure 3.1a shows supply reliability while Figure 3.1b shows pumping use for D = 0.8, $S_{max} = 0.5$, $C_{max} = 1.0$ and streamflow case 3 (Table 3.1).

The upper solid curve in Fig. 3.1a is the empirical cumulative probability that 80% of the demand is satisfied. The curve is stepped because integer numbers of years where demand was satisfied were recorded; for example, this empirical cumulative distribution function (ECDF) indicates that in 40 per cent of flow situations there is at least one year where 80% of the demand is not satisfied. This also means that in 60% of all flow sequences generated, 80% of the demand was supplied in all 40 years of operation. There is a 6% chance that in greater than 90% of the years 80% of the demand will be satisfied. (Here the number of years = 0.9 * 40 = 36.) The worst situation shown indicates that for one particular flow sequence in 0.8 * 40 = 32 years 80% of the demand was satisfied. This means that for

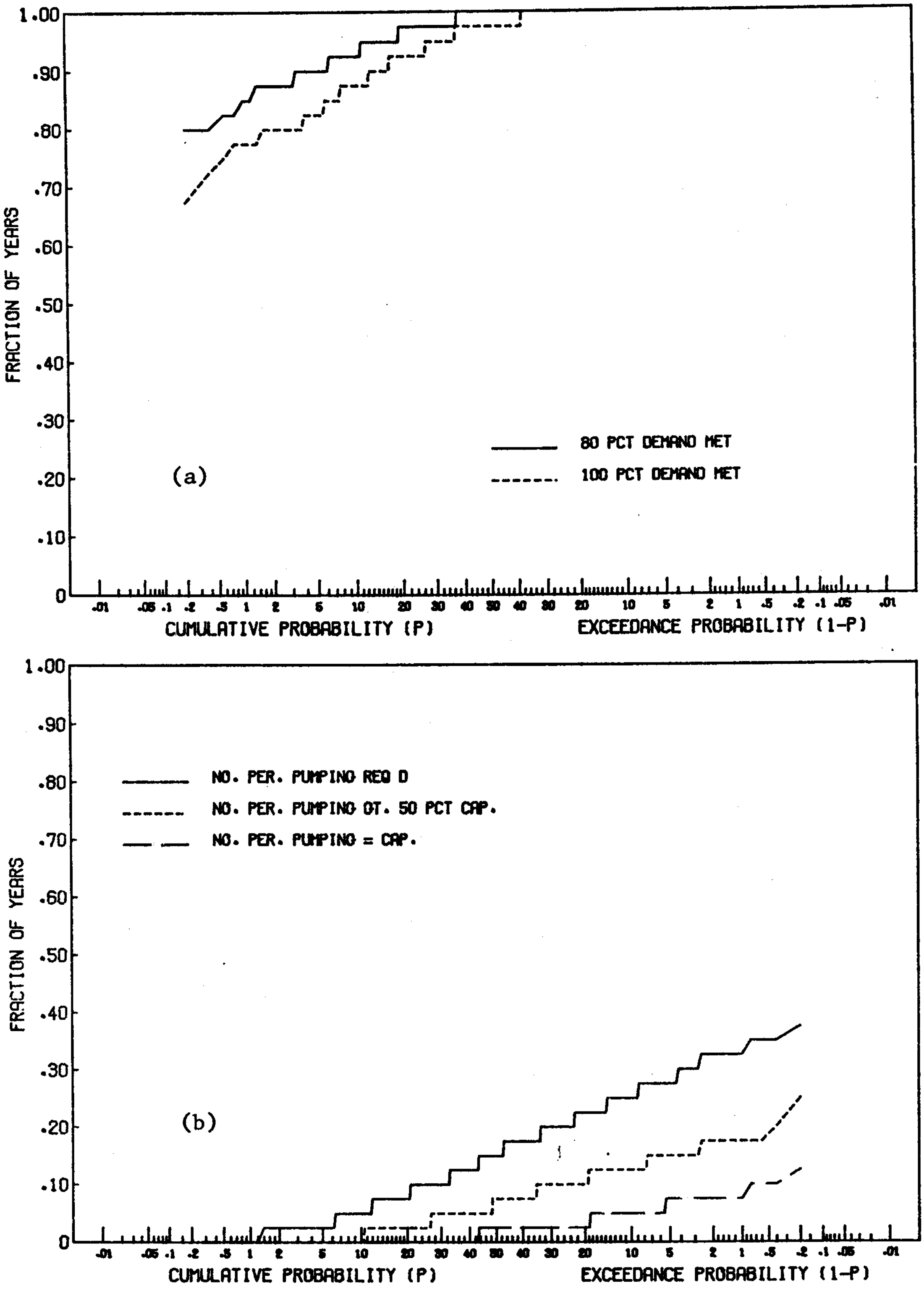


Fig. 3.1 Streamflow Case 3 (H = 0.5, ρ(1) = 0.2, CV = 0.5, skew = 1.0); Demand = 0.8, S_{max} = 0.5, C_{max} = 1.0;

a) Supply summary cumulative distribution
b) Pumping summary cumulative distribution

the particular sequence there were eight years in which there was a significant supply shortfall from the target demand. The solid curve shows the result for satisfying demand fully; the difference between the two curves gives an indication of the severity of supply shortfalls. The reader should note that the bottom probability scale is distorted and is the scale for the normal probability distribution; a straight line appearing on the figure would correspond to a normal distribution. This scale is used only because it amplifies the extreme events such as are of interest in reliability studies; there is no reason to suppose that any of the performance measures investigated are normally distributed.

Figure 3.1b is read in similar fashion to Fig. 3.1a. For example, the upper curve in Fig. 3.1b indicates that for 1.2% of the flow sequences, pumping was not required; there were six sequences where demand was supplied from the surface reservoir alone. The bottom curve indicates the number of periods that pumping was at full capacity. The results of the simulation experiments for the 32 parameter combinations examined were summarized using plots similar to Figs. 3.1a and b.

The reason for computing ECDF's for both the number of periods for which 100% and 80% of target demand was satisfied was to illustrate inherent system ability to satisfy the great bulk of demand even under severe drought conditions. It is well known that during severe drought, careful management of water use usually permits normal economic activity to proceed undiminished under some supply reduction; recent experience in the Western states indicates that a 20% supply shortfall can often be sustained with minimum economic impact. In normal years, of course, less attention is paid to tight management practices; the case may be made that this slack in the nominal demand provides another form of system buffering.

Results

Case 1 Streamflow

The results for this streamflow population are given in Fig. 3.2 for demand equal to 80% of the mean annual streamflow (D = 0.8) and Fig. 3.3 for D = 0.5. This streamflow population produced the most severe droughts of any of the sequences used. Previous work by Lettenmaier and Burges (1977) showed that for a persistence structure corresponding to a Hurst coefficient, H = 0.8, and marginal distribution having variability equal to that used here, a single surface reservoir would have to be impracticably large to satisfy demands between D = 0.5 and D = 0.9. (For D = 0.5 storages greater than about five times the mean flow would be required and for D = 0.7 this number becomes about nine times the mean flow for a reliability of approximately 98%). Therefore it is to be expected that none of the combinations of sizes used here will provide a system having high reliability when D = 0.8 for this streamflow case.

Figure 3.2 shows the relative usefulness of the aquifer in providing water to augment surface water releases. Figure 3.2a indicates that the system has far too little storage to provide any degree of reliability. Because surface storage is quite small considerable pumping occurs and occasionally pumping reaches capacity; most system failures result, however, from emptying of both the surface and aquifer storage.

Figure 3.2b ($S_{max} = 2.0$) shows an improvement in supply reliability and reduced pumping relative to the case having $S_{max} = 0.5$ (Fig. 3.2a). Figure 3.2c shows the results for the same surface storage conditions as Fig. 3.2a but the aquifer capacity is increased from $C_{max} = 1.0$ to $C_{max} = 3.0$. There is an improvement in supply reliability and a substantial increase in pumping from the larger aquifer. Again, however, the combination has insufficient total storage to provide a reliable supply.

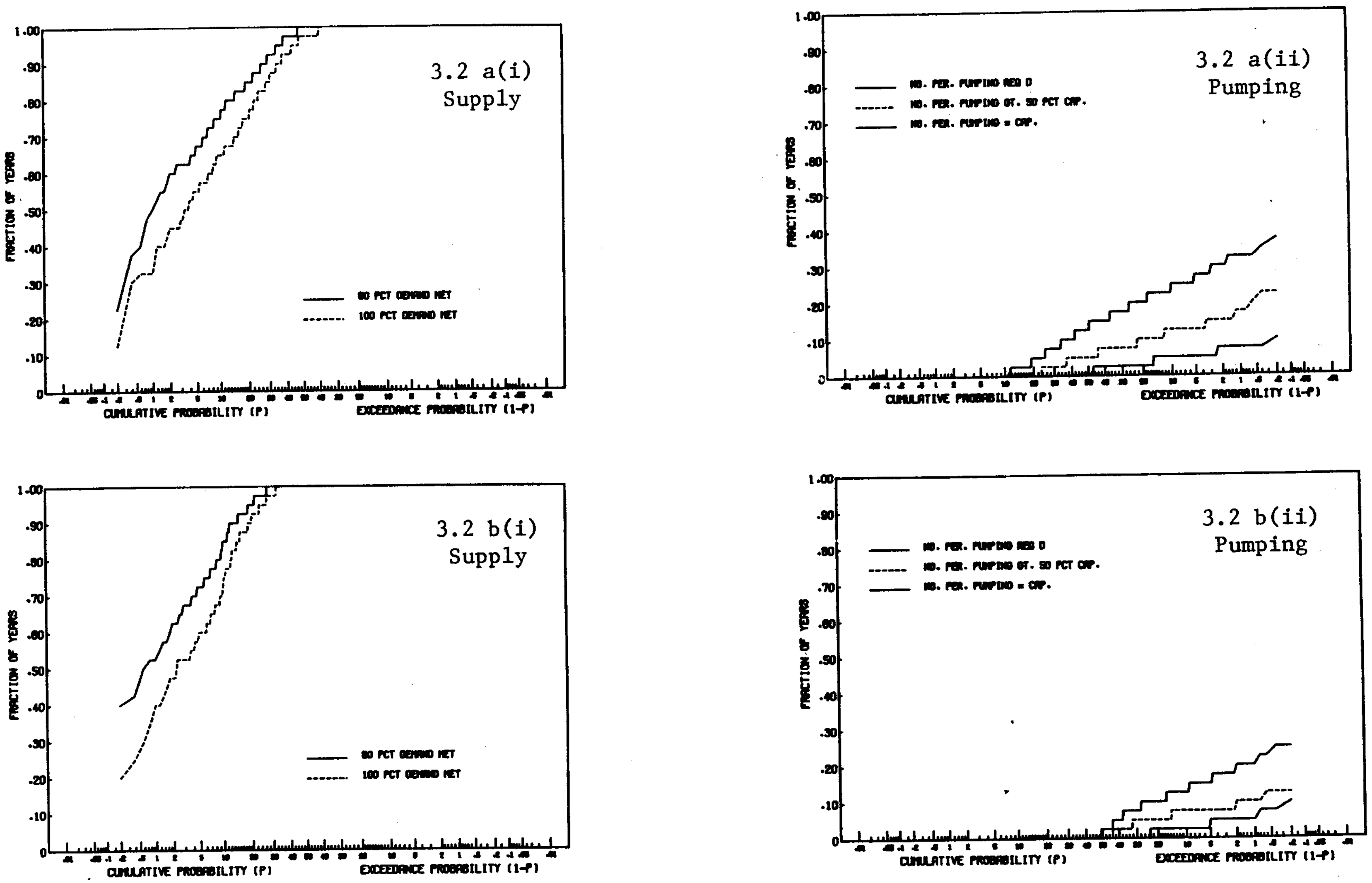


Figure 3.2 Cumulative Distributions Summarizing Supply and Pumping Characteristics for Streamflow Case 1 (H = 0.8, $\rho(1)$ = 0.4, CV - 0.5, Skew = 1.0); Demand = 0.8 (a) $S_{max} = 0.5$, $C_{max} = 1.0$; (b) $S_{max} = 2.0$, $C_{max} = 1.0$.

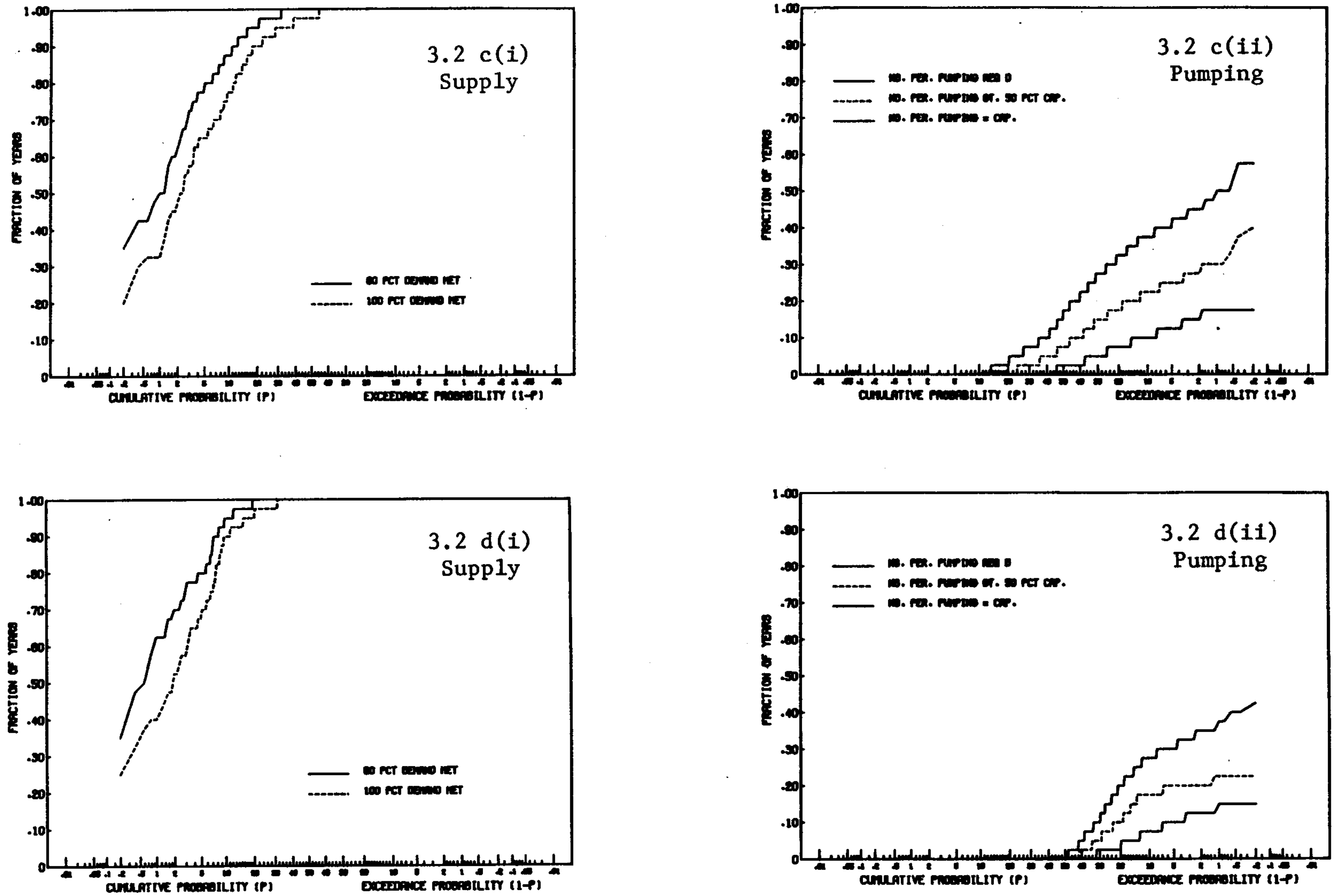


Figure 3.2 (Continued) - (c) $S_{max} = 0.5$, $C_{max} = 3.0$; (d) $S_{max} = 2.0$, $C_{max} = 3.0$.

Results for the largest combination of surface and aquifer storages ($S_{max} = 2.0$, $C_{max} = 3.0$) are shown in Fig. 3.2b. This system gives the best supply reliability for streamflow case 1. Pumping is less than that shown in Fig. 3.2c; it is clear that the major contribution to supply comes from use of the surface reservoir in this case. This is not unexpected because the operating rule employed uses water from the surface reservoir before using aquifer water.

None of the size combinations used with this streamflow population provides a design that is satisfactory for satisfying the large demand ($D = 0.8$) imposed on the system at commonly accepted reliability levels (e.g., 95-98%). When D is reduced, however, more satisfactory reliability results. This can be seen in Fig. 3.3, which contains the same system sizes used in Fig. 3.2; the only difference is that D is reduced from 0.8 to 0.5. Similar features are displayed here to those in Fig. 3.2. However, although the reliability of the system is improved, robustness still remains a problem. Here, robustness is reflected in the severity of failures when they occur, and is given by the steepness of the ECDF; for example, in Fig. 3.3a, even though there is almost a 95% probability of no failure occurring during the 40 year project life, there is about a 0.5% chance that the demand could only be met in 60% of the project life, i.e., that in 16 years of the 40 year life the demand could not be met. Although the approximate 95% reliability of this system might be perceived as adequate, the risk associated with such severe failures might well be unacceptable.

An increase in surface storage from $S_{max} = 0.5$ to 2.0 produces an overall increase in reliability to 98% (Figures 3.3b). Here the larger surface storage reservoir has sufficient size to need only occasional assistance from aquifer pumping to meet demand; severe shortages are, however, still possible.

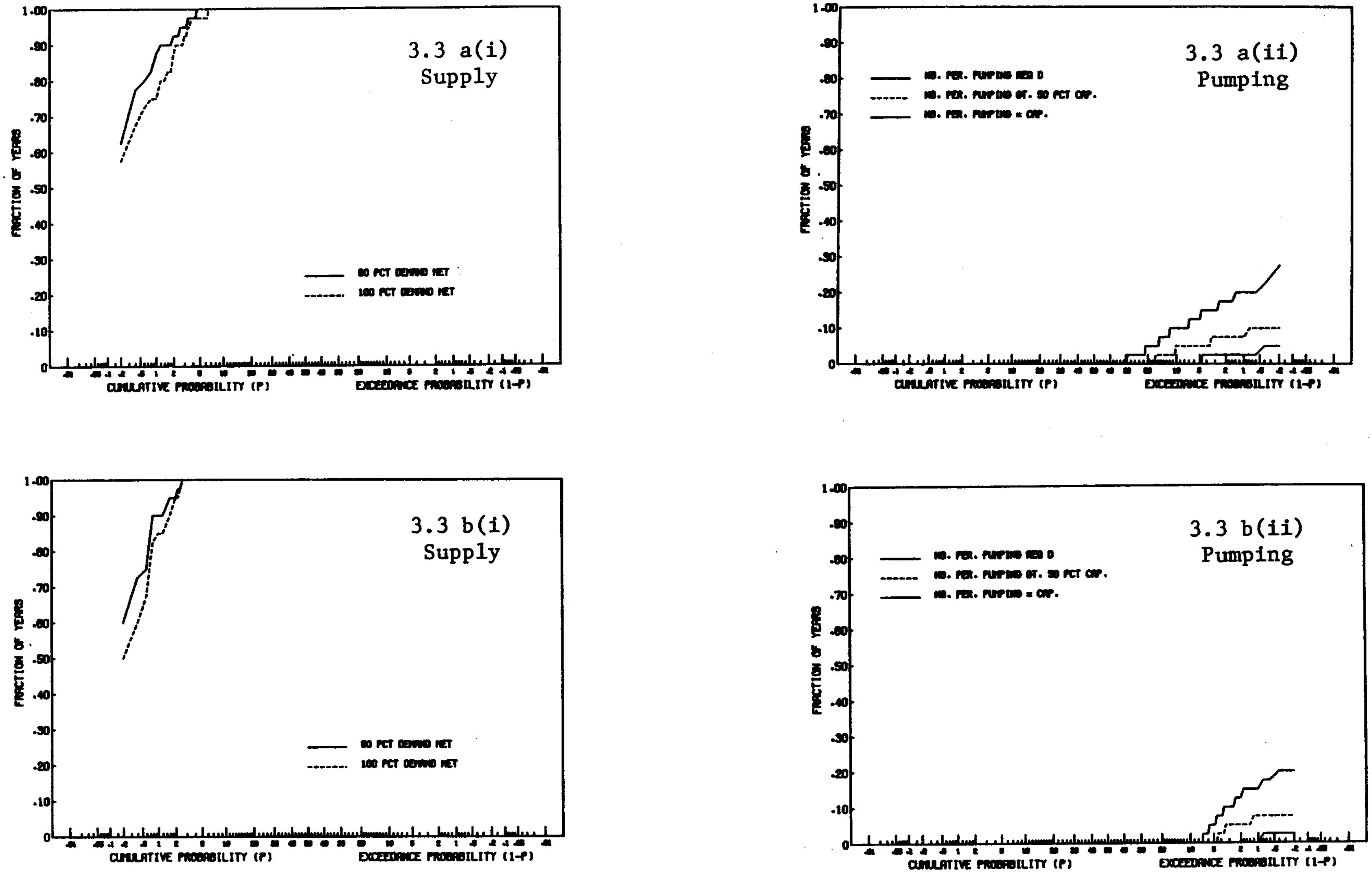


Figure 3.3 Cumulative Distributions Summarizing Supply and Pumping Characteristics for Streamflow Case 1 ($H = 0.8$, $\rho(1) = 0.4$, $CV = 0.5$, $Skew = 1.0$); Demand = 0.5 (a) $S_{max} = 0.5$, $C_{max} = 1.0$; (b) $S_{max} = 2.0$, $C_{max} = 1.0$.

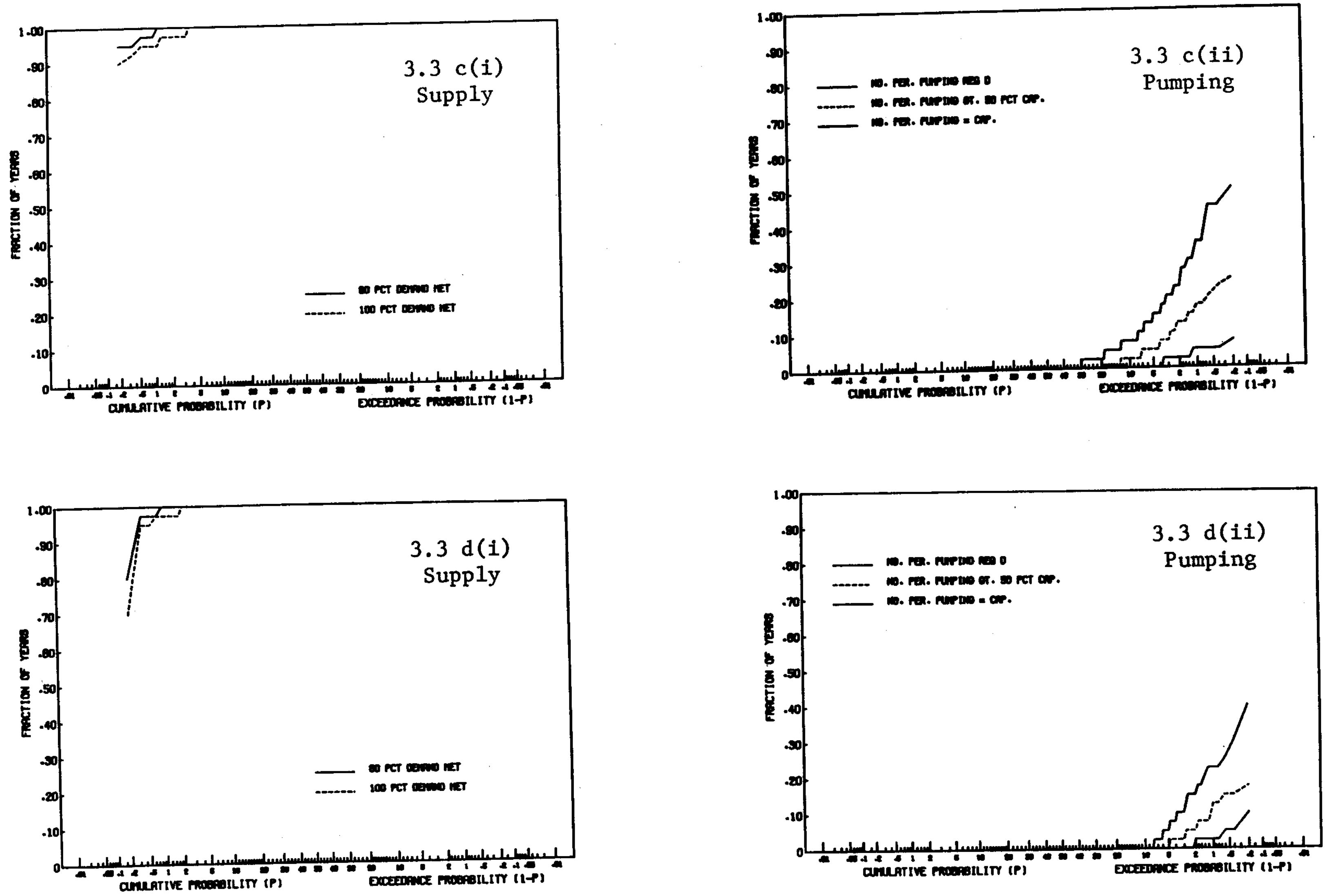


Figure 3.3 (Continued) - (c) $S_{max} = 0.5$, $C_{max} = 3.0$; (d) $S_{max} = 2.0$, $C_{max} = 3.0$.

A small reservoir and large aquifer combination (Figures 3.3c) is clearly satisfactory, providing a supply reliability, for meeting 80% of D in excess of 99%. The importance of pumping to make up the deficit in years of extreme low flow is clear. For this particular case some recharge was effected for 27% of the flow sequences. In 16% of the flow sequences recharge occurred in two or more years and for 4% of the sequences recharge occurred in more than four years. In only 3% of the flow sequences was recharge greater than 50% of capacity, in at least one year. It may thus be concluded that recharge is not a limiting feature with this system. The minimum aquifer storage was less than 50% of capacity for only 2 percent of the flow sequences and was only drawn upon in 29% of all sequences. The longest period that aquifer storage was less than 50% of capacity was seven years. It is apparent here that it is the large size of the aquifer storage which controls system performance.

Figure 3.3d shows an even more reliable system where surface storage is $S_{max} = 2.0$. The added increment of surface storage over that in Fig. 3.3c is of little benefit and would most likely be uneconomical. The system is apparently less robust than the equivalent system with $S_{max} = 0.5$ which is counterintuitive. However, the extreme left tail in the supply ECDF's of Fig. 3.3d is the result of only a single flow sequence (out of the 500 investigated) and probably reflects statistical sampling variability rather than a real difference.

Case 2 Streamflow

This streamflow population has the same variability and skewness as Case 1 but has a lower value of H and hence less severe and lengthy droughts. Figure 3.4 shows the results for this streamflow scenario for the same system configurations considered in Fig. 3.3a for streamflow case 1.

The overall features displayed in Fig. 3.4 do not differ appreciably from those shown in Fig. 3.3. However, while overall reliabilities are similar

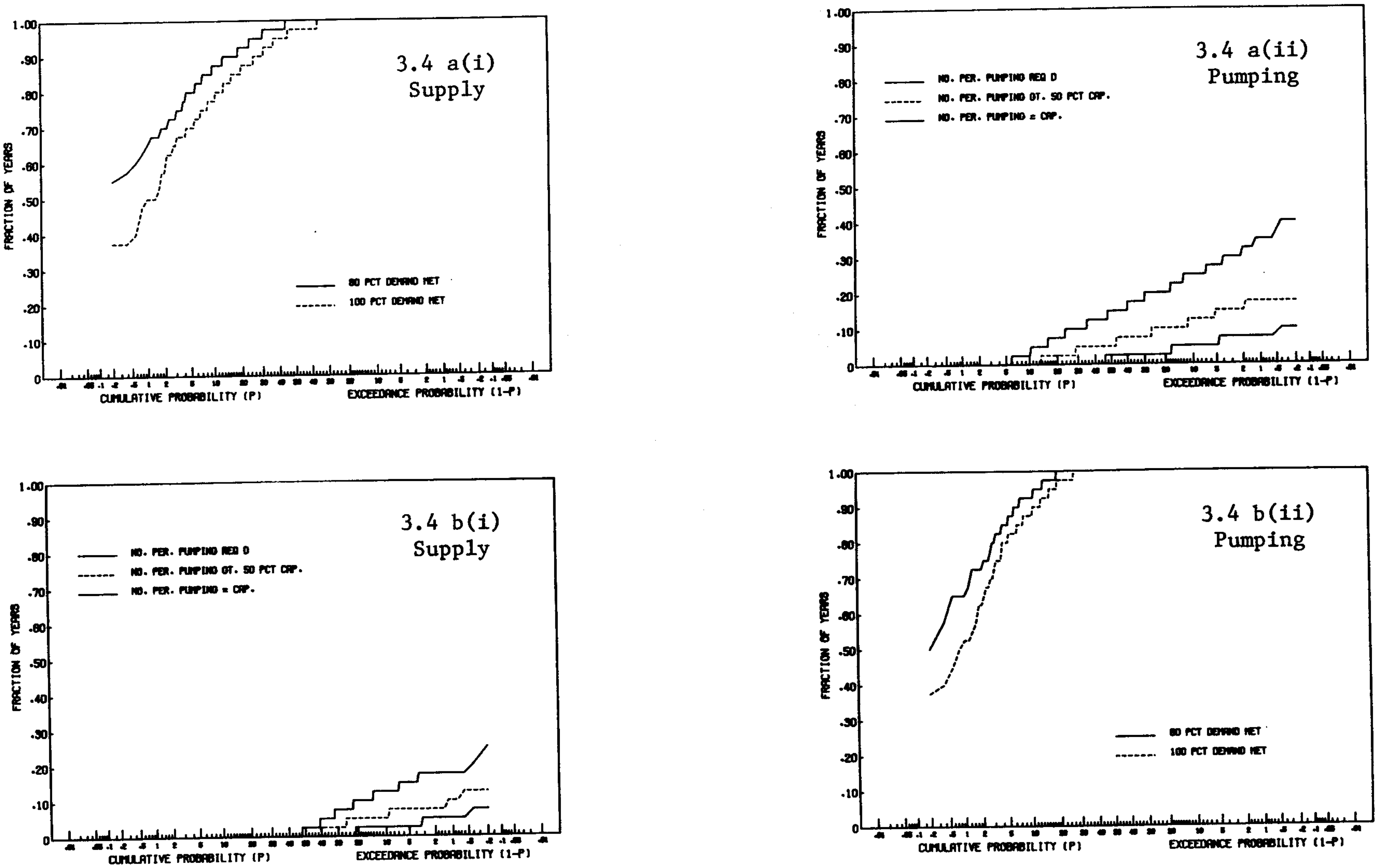


Figure 3.4 Cumulative Distributions Summarizing Supply and Pumping Characteristics for Streamflow Case 2 ($H = 0.7$, $\rho(1) = 0.2$, $CV = 0.5$, Skew $= 1.0$); Demand $= 0.8$ (a) $S_{max} = 0.5$, $C_{max} = 1.0$; (b) $S_{max} = 2.0$, $C_{max} = 1.0$.

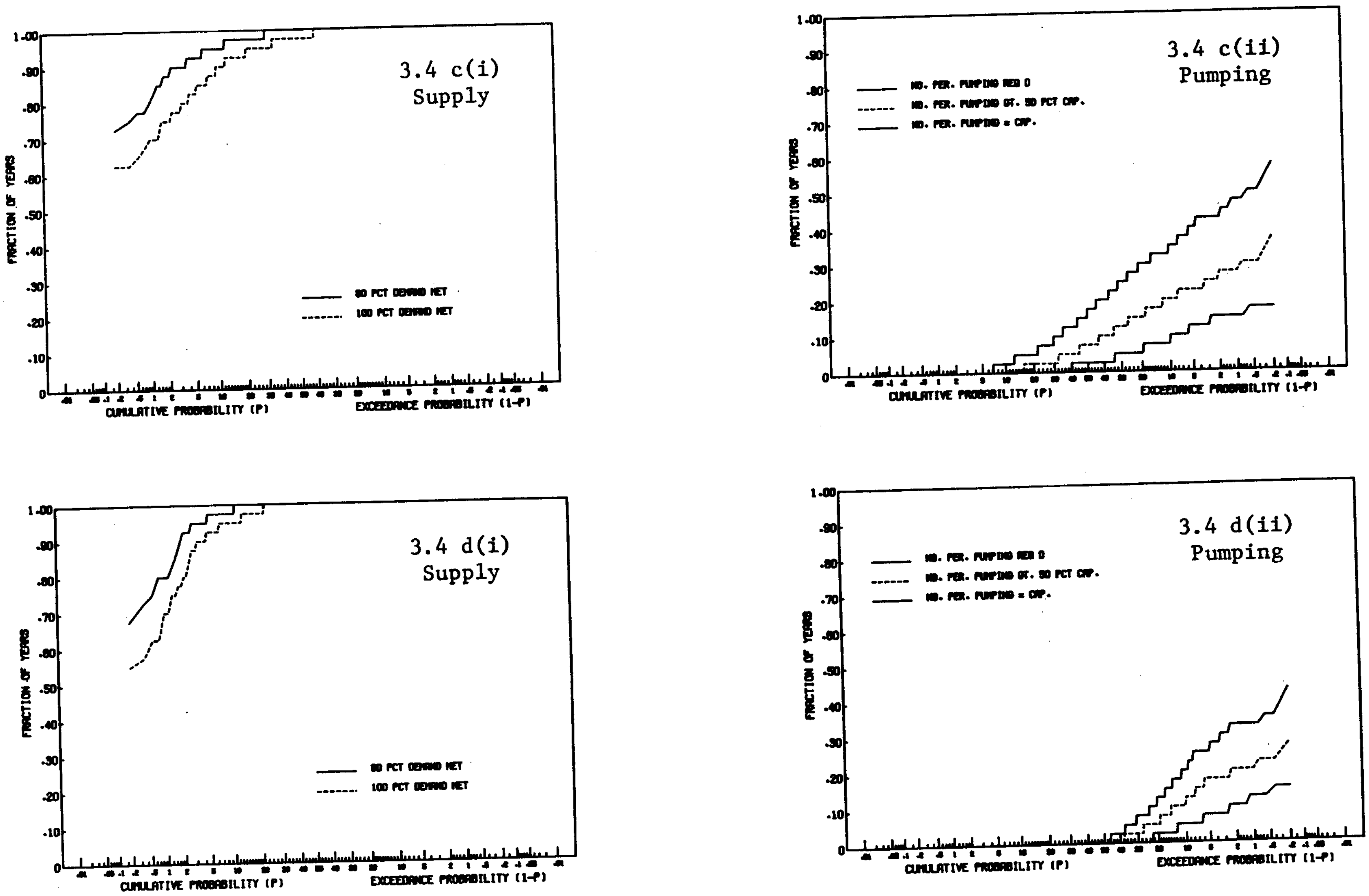


Figure 3.4 (Continued) - (c) $S_{max} = 0.5$, $C_{max} = 3.0$; (d) $S_{max} = 2.0$, $C_{max} = 3.0$.

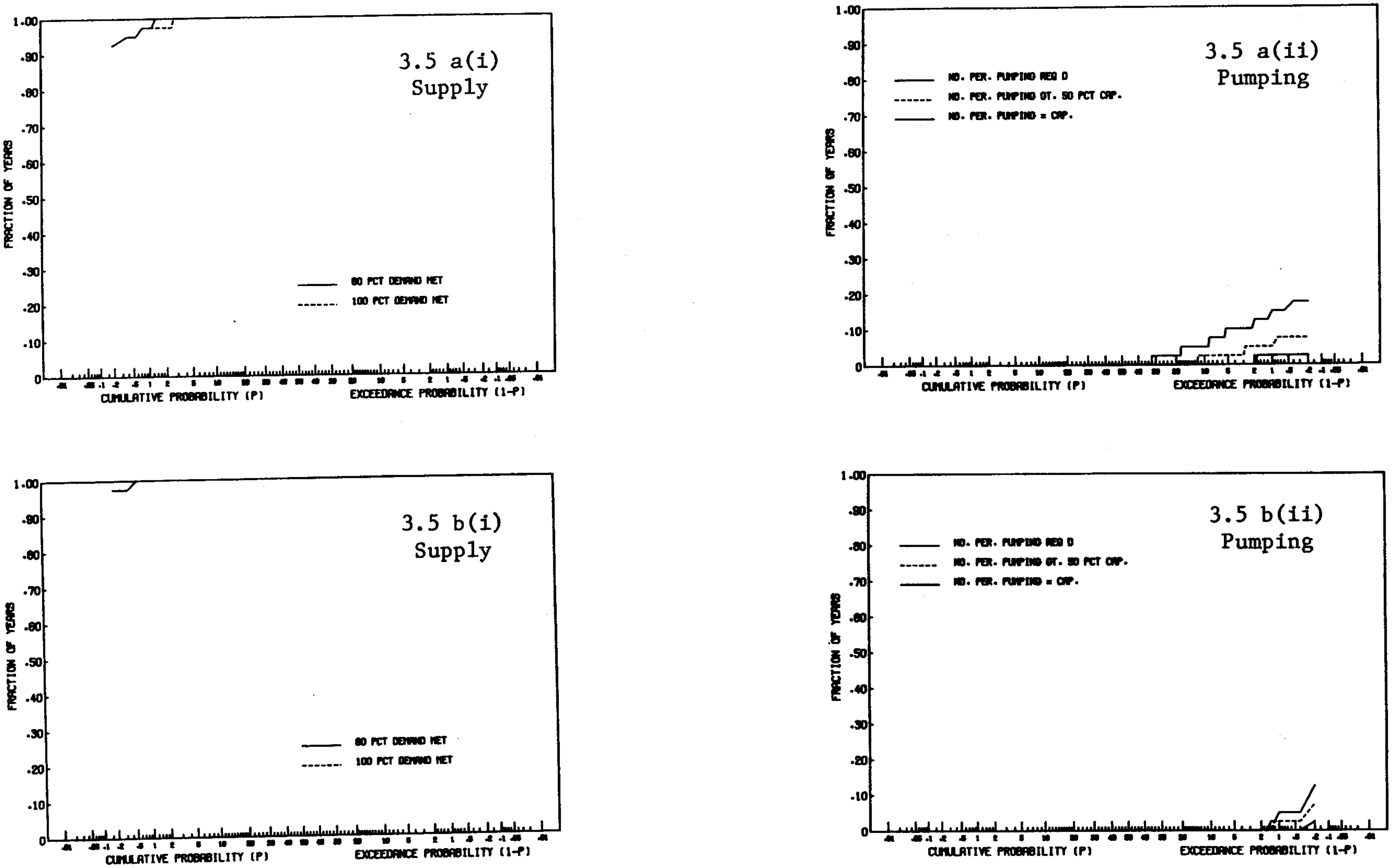


Figure 3.5 Cumulative Distributions Summarizing Supply and Pumping Characteristics for Streamflow Case 2 (H = 0.7, $\rho(1)$ = 0.2, CV = 0.5, Skew = 1.0); Demand = 0.5 (a) S_{max} = 0.5, C_{max} = 1.0; (b) S_{max} = 2.0, C_{max} = 1.0.

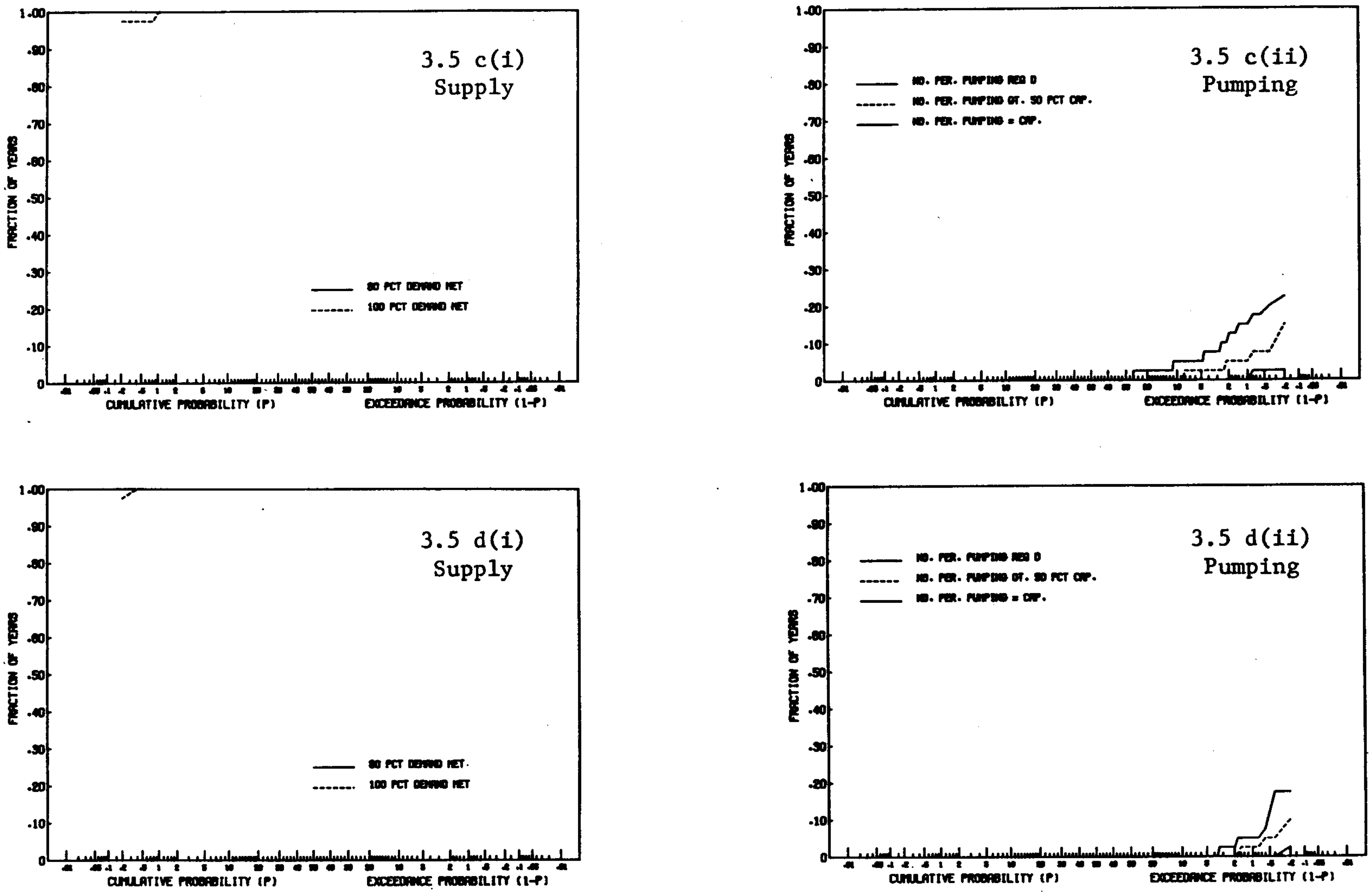


Figure 3.5 (Continued) - (c) $S_{max} = 0.5$, $C_{max} = 3.0$; (d) $S_{max} = 2.0$, $C_{max} = 3.0$.

for the two streamflow populations, the severity of supply shortfalls is more pronounced in Fig. 3.2 than in Fig. 3.4 for the same demand levels; the latter system is more robust. Pumping behaviors are quite similar for both cases.

For the lower demand D = 0.5 (Fig. 3.5) system size combinations are all seen to be more robust in their supply capability than for more persistent streamflows (Fig. 3.3). It appears that a satisfactory design would result for this streamflow scenario and demand level for the combination $S_{max} = 0.5$; $C_{max} = 1.0$ (Fig. 3.5a). Pumping in all cases is less than for comparable situations shown in Fig. 3.3. The results shown in Fig. 3.5a correspond to pumping for 32 percent of all inflow sequences. The minimum aquifer content fell to 0.8 for 15 percent of the sequences and to 0.5 for 4 percent of the inflow sequences. Aquifer drawdown corresponding to Fig. 3.5c ($S_{max} = 0.5$; $C_{max} = 3.0$) was generally less indicating that the recharge to capacity (I_{max}/C_{max}) ratio may be an important descriptor of system performance.

Case 3 Streamflow

This streamflow population exhibits only short-term persistence and usually exhibits droughts of only a few years maximum duration. The variability and skewness are the same as streamflow cases 1 and 2. The general shapes of the supply and pumping cumulative distributions (Fig. 3.6) are similar to those of Figs. 3.2 and 3.4. The number of years of each flow sequence experiencing shortfalls is, however, considerably smaller than for the first two streamflow populations. The pumping summary information is quite similar to that shown in Figs. 3.2 and 3.4.

It is clear that for $C_{max} = 1.0$, neither the combinations $S_{max} = 0.5$ (Fig. 3.6a) or $S_{max} = 2.0$ (Fig. 3.6b) provide satisfactory reliability for this demand level. The combination $S_{max} = 2.0$, $C_{max} = 3.0$ (Fig. 3.6d) would be marginally satisfactory, however, having a shortfall of more than 20 percent of the target demand in one year in forty for fewer than 6 percent of all inflow

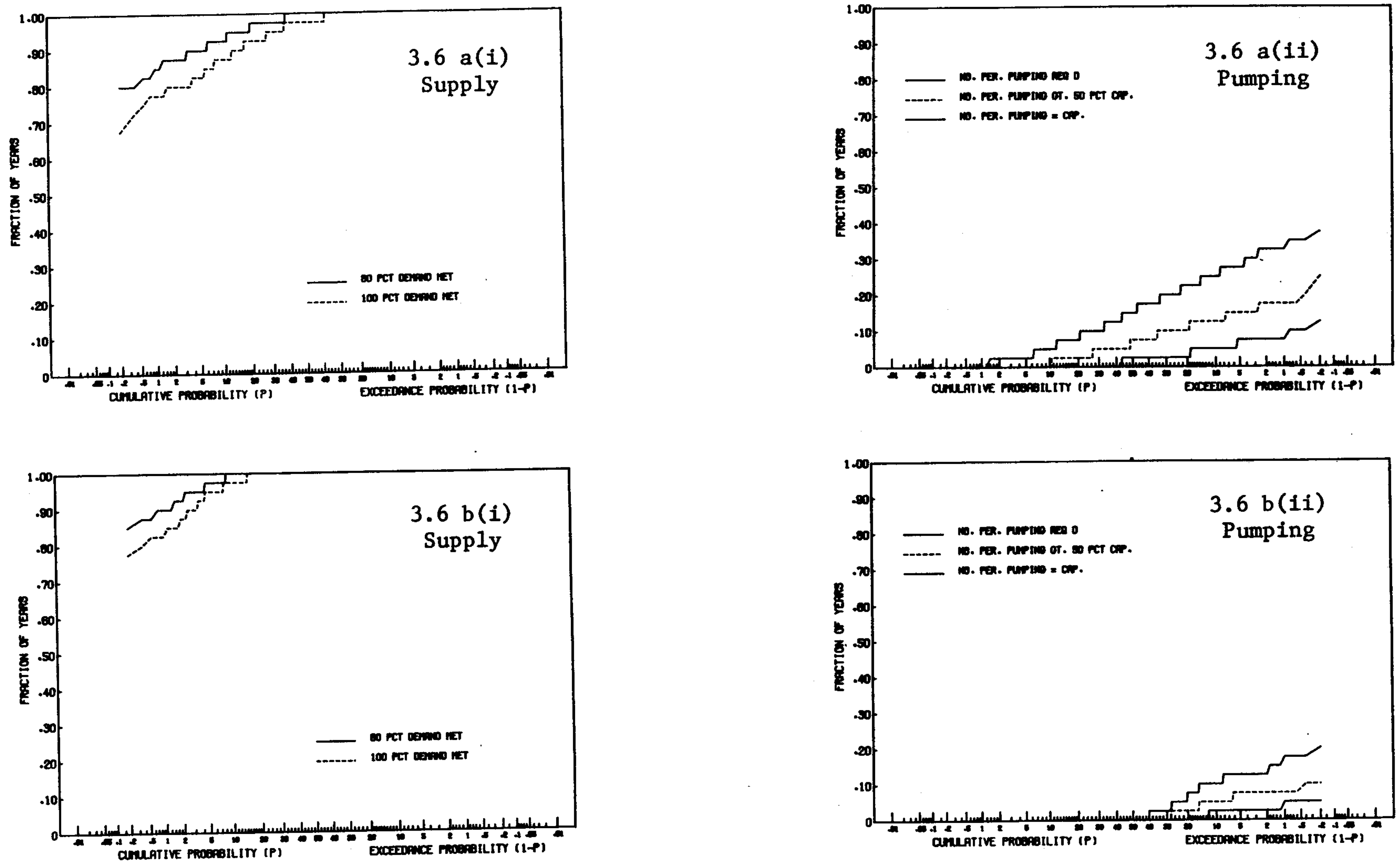
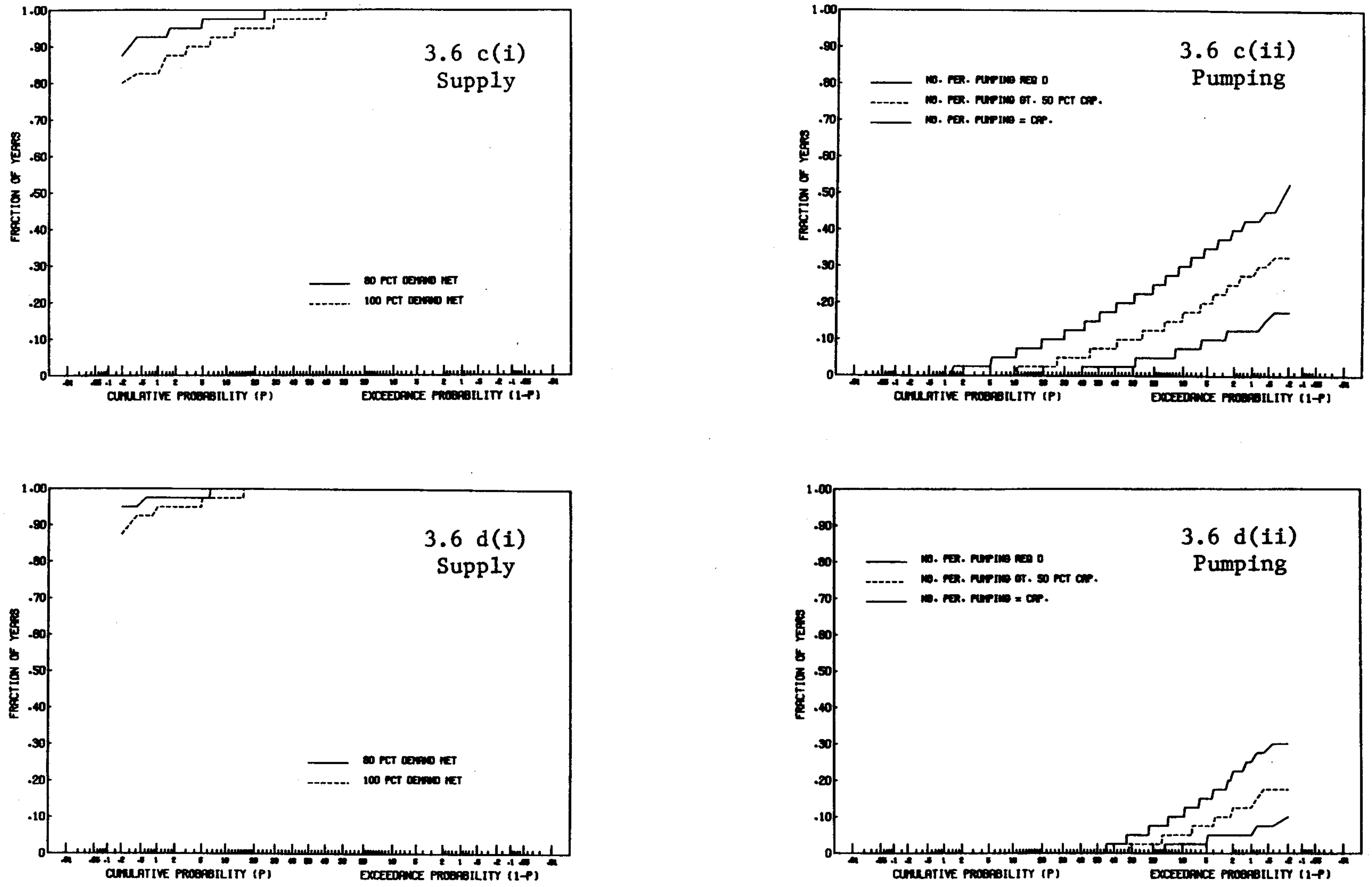


Figure 3.6 Cumulative Distributions Summarizing Supply and Pumping Characteristics for Streamflow Case 3 (H = 0.5, $\rho(1) = 0.2$, CV = 0.5, Skew = 1.0); Demand = 0.8 (a) $S_{max} = 0.5$, $C_{max} = 1.0$; (b) $S_{max} = 2.0$, $C_{max} = 1.0$.



3.6 c(i)
Supply

3.6 c(ii)
Pumping

3.6 d(i)
Supply

3.6 d(ii)
Pumping

Figure 3.6 (Continued) - (c) $S_{max} = 0.5$, $C_{max} = 3.0$; (d) $S_{max} = 2.0$, $C_{max} = 3.0$.

sequences. Our assumed (large) maximum recharge capacity $I_{max} = 1.0$, may be at issue here. Analysis of additional summary data showed that 10% of all flow sequences gave rise to recharge in excess of 50% of I_{max}, for 25% of all sequences recharge was effected in more than two years, and for 10% of flow sequences recharge was effected in more than three years. For 1% of all sequences the aquifer contents were less than 50% of capacity for 14 years or longer, while for 97% of the flow sequences the aquifer storage always exceeded 50% of capacity.

For demand level D = 0.5 the results were comparable to those shown in Fig. 3.5 but provide greater reliability and require less pumping for each size combination. We have not presented results for this case here because little would be added to the information displayed in Fig. 3.5. Generally, either system configuration would provide high reliability.

Case 4 Streamflow

This flow scenario was the most benign considered, having only short-term persistence and low variability of the marginal distribution. The capacity combinations considered all would provide high reliability for either D = 0.5 or 0.8. For the higher demand level and low storage ($S_{max} = 0.5$; $C_{max} = 1.0$) configuration some pumping was required in a maximum of nine of forty years, and 80 percent of demand could be met for 99.5% of all sequences generated. For this configuration there was a maximum of only one year in forty that the shortfall in supply exceeded 20 percent of the target demand. This is not surprising in light of results given by Burges and Linsley (1971) who showed that for this streamflow case a single surface reservoir having $S_{max} = 0.5$ could meet a demand D = 0.7 fully for 80 percent of all possible sequences of length 40. The present results do indicate, however, the degrees of interaction between the two storages which was not known previously.

Reduction of demand to D = 0.5 results in a highly reliable system that is of relatively little interest in the present study. For this streamflow scenario, storage was far larger than required so the design would quite likely be uneconomic; in a more detailed study one might well desire to investigate the possibility of eliminating the surface reservoir altogether (see Chapter 4).

Summary

Interrelationships between streamflow stochasticity, surface storage reservoir and aquifer capacities, and target demand have been illustrated. It is clear that it is practically infeasible to develop a cyclic storage system for extremely persistent and variable streamflow (case 1) that can supply a demand as large as 80 percent of the mean annual streamflow when stringent performance criteria are used.

By using a surface water reservoir with capacity as large as twice the mean annual flow,coupled with an aquifer that has capacity as large as three times the mean annual flow,demands of 50 percent of the mean flow can be met satisfactorily for an extensive range of streamflow stochastic features. It must be recognized that the results shown here reflect the upper limit of performance because seasonal restrictions on recharge magnitude, issues of ground subsidence from pumping, etc., have not been examined.

The results shown here are for physical considerations; it is also important to examine economic (cost) features and other nontechnical considerations to assess cyclic storage feasibility. These issues are addressed in Chapters 4 and 5.

Chapter 4

ECONOMIC ANALYSIS

In Chapter 3 we have analyzed the physical performance of various surface-aquifer storage combinations and demand levels. The aim of this analysis was to gain insight into the relative importance of the parameters affecting system performance at several levels of the controlling variables. In application, however, many of the parameters, such as aquifer size, reservoir inflow stream characteristics, etc., are fixed. Here it is desired to select a design which combines the remaining parameters over which the designer has some control (e.g., surface reservoir size, pumping capacity, and possibly recharge capacity) in such a manner as to meet given performance standards. This is to be done while maximizing (or minimizing) the components of an objective function or, perhaps, multiple objective functions. The variables in the objective function might include economic measures such as net benefits or total cost as well as equity (distribution of payment burden), environmental consequences, sociological impact, etc. If the objective of the system is to provide water supply, the performance measure will normally be related to the reliability of the system in meeting a given set of demand projections.

Cost Estimates

In this work we consider a univariate objective function, namely total system cost. The alternate economic measure, net benefits (or benefit/cost ratio) was not used since estimation of benefits is substantially more time consuming than estimating costs (Howe, 1971) and because benefits are usually site-specific. Specific site analysis was beyond the scope of the present project and would have diverted attention from the general characteristics of parameter interactions which we desire to identify here.

Total system cost elements were:

a) surface reservoir capital cost,

b) surface reservoir operation, maintenance, and repair costs,

c) well drilling, pump purchase, and installation cost,

d) pump maintenance, cost, and

e) pumping energy cost

Installation costs for the distribution system which would be necessary to effect a cyclic storage system were not considered. We assumed that supply from the surface reservoir to the demand point is possible by gravity feed and that the same distribution system could be used for aquifer recharge. Essentially, neglecting distribution costs for comparative purposes is analogous to a more reasonable assumption that the cost of the distribution system under the various surface storage/pumping capacity combinations considered is the same. For the present purposes, and particularly in light of the results achieved, such an assumption seems justifiable.

Specific cost ranges were estimated as follows:

a) Surface reservoir construction and related costs: Maass, et al. (1962) give surface reservoir cost curves which cover the approximate range \$15-45/AF. These costs are applicable to moderate to large earth fill impoundments, for instance larger than about 50,000 AF. These figures were assumed to be applicable to year 1960, the approximate date of the preparation of the reference, and were updated to present by multipliers in the range 2-3, suggesting an approximate current range of \$30-150/AF. An additional consideration is that many remaining surface storage sites are more costly to develop than those previously available, both because of the increased cost displacement of alternate users of areas which would be inundated and because of increased costs associated with site-specific problems which may have precluded earlier development in favor of cheaper sites. A more realistic cost range which reflects these problems as well was taken to be \$60-300/AF. An independent check is provided by Ambroggi (1978) who states that "The cost of regulating a cubic kilometer of water by the dam-reservoir method now amounts to about \$100 million ..." (\$137/AF) which falls slightly below the midpoint of the estimated range.

b) Surface reservoir OMR: Maass, et al. (1962) show, for the same systems for which capital costs were estimated, annual OMR in the range \$.005 - .05/AF. Updating these to the present using the same multipliers as were used for construction costs (but not the additional correction for specific site construction difficulties, which should have a much smaller effect on OMR) a range of \$.01 - .15/AF results.

c) Well drilling and pump purchase: These costs were estimated on the basis of information provided by Mr. John Raymond of Battelle Northwest and Mr. Eugene Hall of Hall Pump and Irrigation Co., Yakima, Washington. Mr. Raymond and Mr. Hall have been involved in the planning and construction aspects, respectively of groundwater development activities in the Yakima basin, particularly during the 1977 Northwest drought. Base costs were estimated for 16" diameter wells with pumping facilities capable of delivering 3000 gpm. Well drilling and casing costs were estimated to be in the range \$2.75 - 3.50/in. diameter/ft. depth, or approximately \$45 - 55 per foot for the 16" casing of interest. Approximately \$1250 was allowed for the electrical set (meter, power panel, conduit, etc.) with additional labor costs of \$1.50 - 2.00 per foot well depth for line shaft pump installation. Use of electrically driven pumps is considered here since current energy pricing, especially in the Northwest, favors its use in place of fossil fuels. Pump purchase cost was estimated on the basis of a 300 HP motor (capable of delivering 3000 gpm at 300 ft. head with efficiency 0.80) and 320 foot bowl depth. Approximate purchase price of such a unit is \$25,000. For modeling purposes, pump purchase and installation cost was treated separately from well drilling and casing. The latter was estimated using the midpoint of the range indicated of $50/AF, while a total purchase and installation cost of $30,000 per unit was used. The purchase and installation cost used is slightly larger than the sum of the components to allow for the possible necessity of power line extension, access improvements, etc.

d) Pump maintenance: Estimated maintenance costs provided by E. Hall were used. Expected pump working life is approximately 20 years with complete overhauls on a four year cycle. Pump overhaul primarily involves replacement of bearings and renewal of electrical components. Overhaul cost is approximately 1/3 of the replacement cost of the bowl, which in turn is about 1/4 of the replacement cost of the pump unit itself. On this basis annual overhaul cost was estimated as one-twelfth of total pump installation and purchase cost (total cost, rather than equipment cost alone was used to provide an allowance for the additional cost of pump removal and installation for servicing).

e) Pump energy cost: Current Northwest power rates were used as a lower bound for energy costs. Current rates for public utility districts are in the range $.01 - .02/Kilowatt hour (KwH). As an upper bound, the cost of new thermal power installation was used; this may range up to $.12/KwH.

Determination of Equivalent Systems

To determine the relative cost of meeting system demand through use of surface and subsurface storage, it is necessary to determine mixes of surface storage size and aquifer size, recharge and pumping capacities which result in the same system performance. In the experiments reported here, aquifer size and recharge capacity were taken as fixed so that the only variables of interest in determining equivalent mixes were surface storage size and capacity. Aquifer size and annual recharge capacity were both taken equal to the mean annual surface reservoir inflow volume. As in the experiments reported in Chapter 3, initial surface reservoir storage was always 20% of capacity and the aquifer storage was always full initially. The large recharge capacity used was selected so that recharge would not be a limiting factor; it is likely that the results would not have been much different unless recharge capacity was reduced to less than one-half of the value used. Annual demand was taken as 0.7 of the mean annual reservoir inflow, with the objective of system operation being to meet the demand as nearly as possible each year.

Initially, it was determined to use the reliability estimates R_{100} and R_{80} described in Chapter 3 as the performance measures. Specifically, R_{100} is the estimated probability of meeting the demand fully and R_{80} is the probability of meeting at least 80% of the demand in all years of any given streamflow scenario of length equal to the project life. These probabilities are estimated as the ratio of the number of synthetically generated sequences in which the criterion is met every year in the (40 year) project life to the total number of synthetically generated inflow sequences (500 were used here). The reliability level often used in the water works industry is 98%, and this was the criterion we initially attempted to use. Imposition of this requirement, however, was found to require unrealistically large storage capacities, e.g., several times the mean reservoir inflow. Similar results were found by Burges and Lettenmaier (1977) for a single surface reservoir. The reason that such large surface storage capacities are required (note that aquifer storage was held fixed, so varying pumping capacity could only affect system performance within a limited range) is that the criterion used is very rigid: The system is assumed to have "failed" for a given streamflow scenario if the demand cannot be satisfied in <u>all</u> years of that sequence. A more operationally realistic definition of reliability is based on the expected system performance for any given trace, such as the expected minimum supply delivered in a given number of years of the project life. This expectation may be determined by a) for each sequence, ranking the actual supply delivered for each year of the project life, b) determining the minimum supply delivered at cumulative probability level $P_j = \frac{j}{(T + 1)}$, where T is the project life and j is the number of years of the project for which the minimum supply delivery is estimated (specifically, the j years during which the system performed most favorably), and c) averaging the minimum supply delivered over the 500 generated sequences. For estimation purposes, the project life, T was taken as 39 rather than 40 years so that convenient empirical probabilities would correspond to even years of record.

The reliability defined in this manner is denoted R_p^*, with p the percentage of years in any given trace for which the criterion is expected to be met. It should also be noted that R_p^* is a function of the project life, as in R_p, however, in this work projects of life 40 only are considered (the small error by using sequences of length 39 rather than 40 for convenience has minimal practical effect, especially for the preliminary analyses conducted here).

To achieve the objective of determining surface storage/pumping capacities mixes with equal performance, R_{95}^* was plotted as a function of pumping capacity for a range of surface storage sizes as shown in Fig. 4.1. Probability level p = 95 (per cent) was selected as a reasonable compromise between the desire to maintain high reliability and the difficulty noted above in estimating tail probabilities from a moderate number of traces. A convenient criterion was found to be a "95/95" rule, i.e., that the expected minimum supply delivered in 95% of the years of record be 95% of the nominal demand. This criterion corresponds to the horizontal line in Fig. 4.1. Figures 4.2 and 4.3 show the R_{80} and R_{100} estimates plotted in the same manner. An

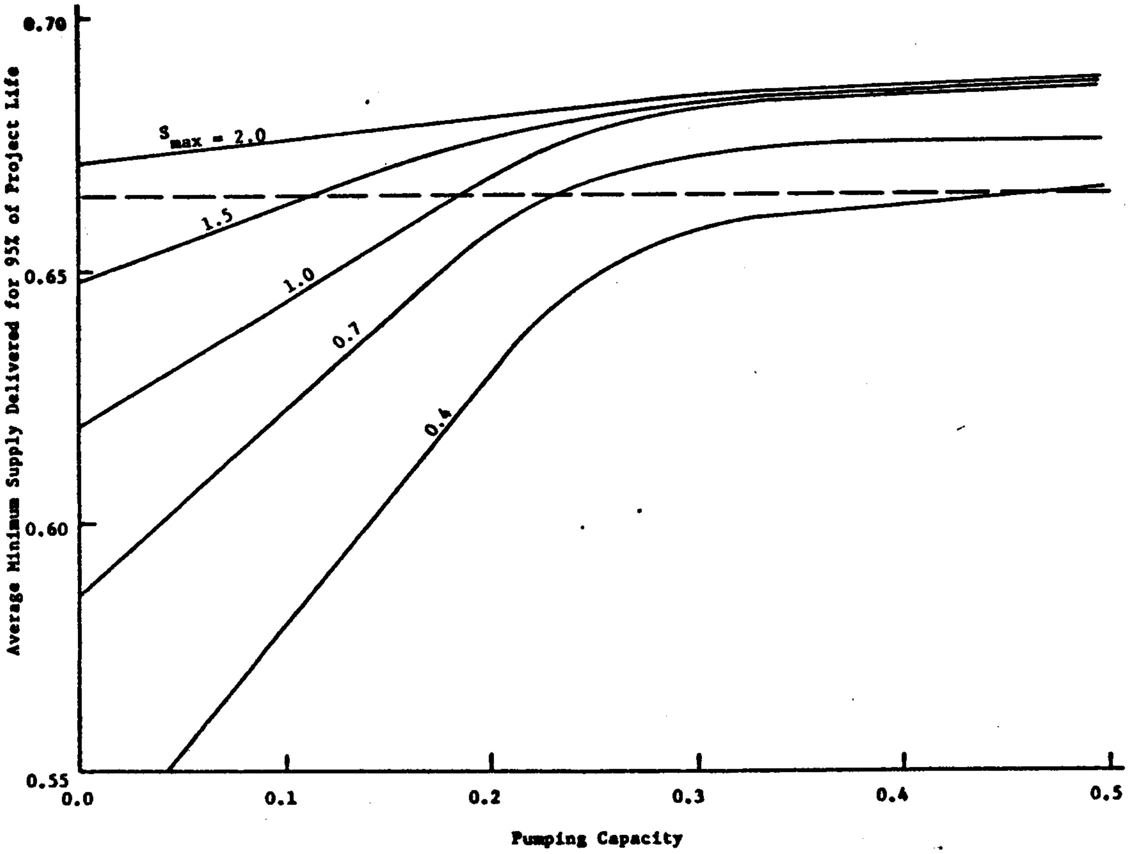


Figure 4.1 R^*_{95}, Average Minimum Supply Delivered for 95% of Project Life vs. Pumping Capacity

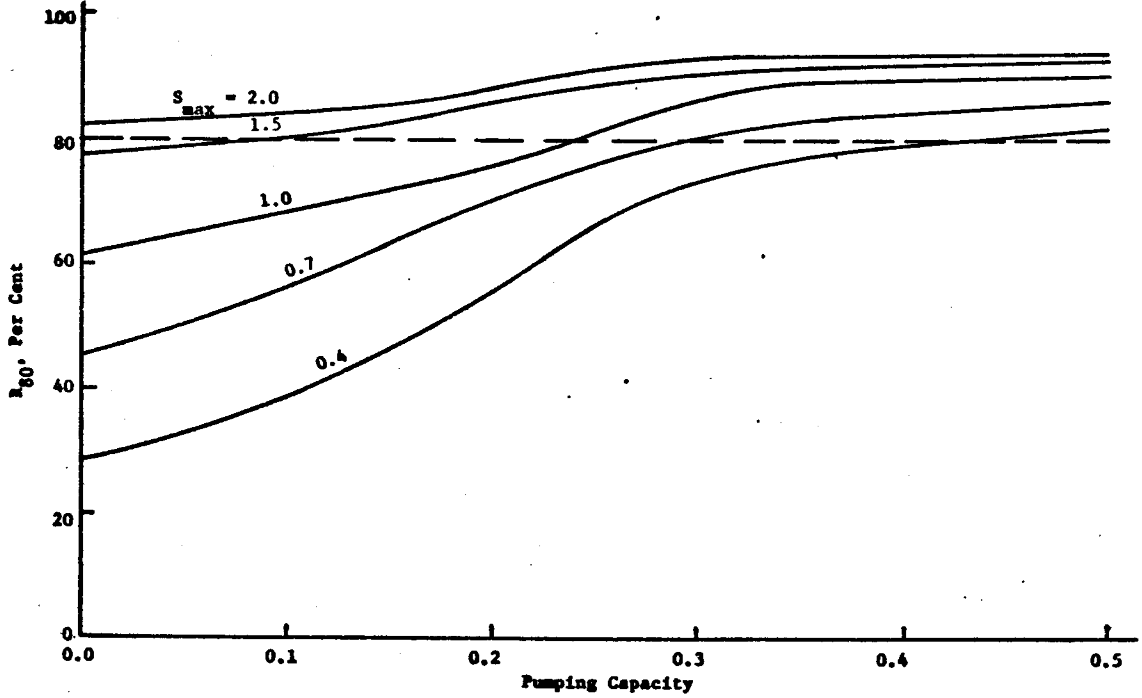


Figure 4.2 R_{80}, Probability of System Performing with no Supply Deficit more Severe than 80% of Demand vs. Pumping Capacity

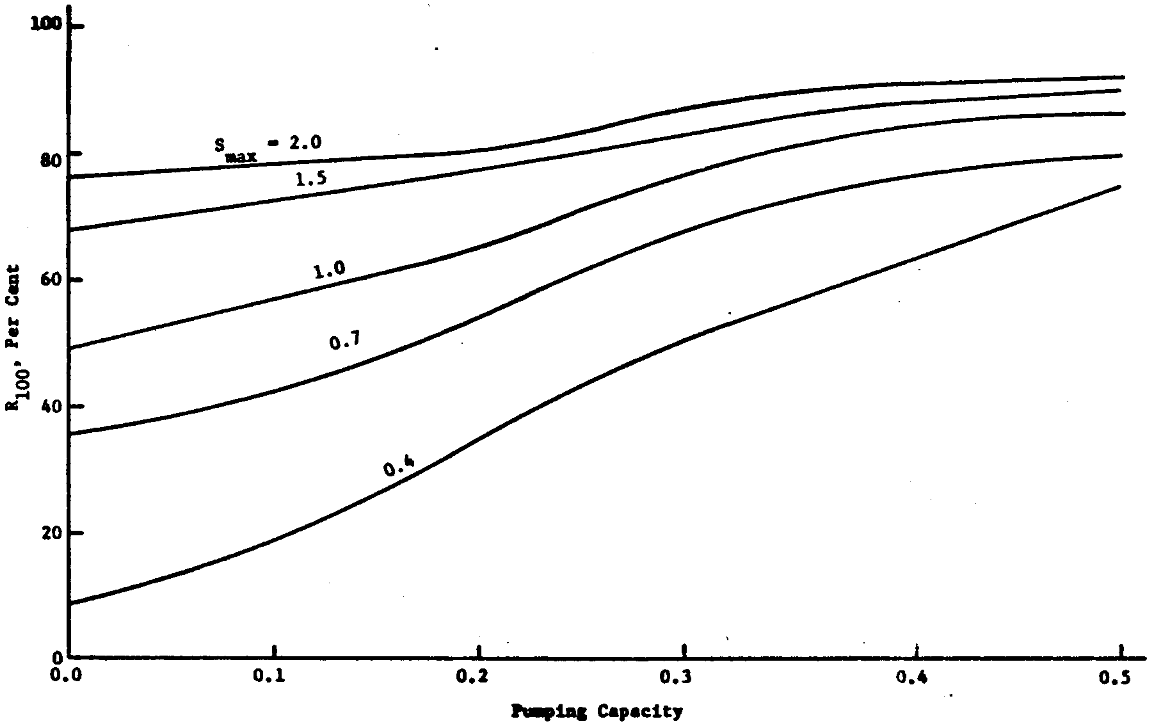


Figure 4.3 R_{100}, Probability of System Performing with no Failures vs. Pumping Capacity

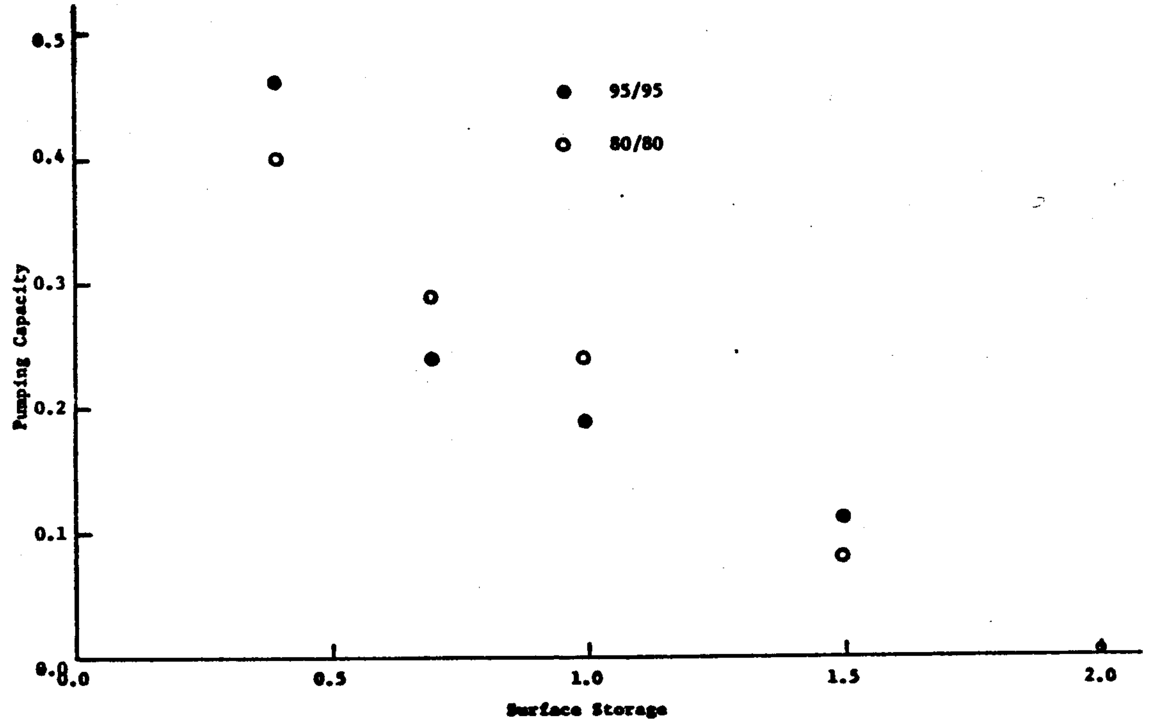


Figure 4.4 Pumping Capacity/Surface Storage Combinations with Equal Performance

alternate criterion considered was an 80/80 rule for R, i.e., that the probability that there be no occurrences of shortages more severe than 80% of the nominal demand for any given reservoir inflow sequence be 80%. The estimated pumping requirements are shown as a function of surface storage in Fig. 4.4. The pumping requirements under the 95/95 and 80/80 criteria are not much different. Also, pumping capacity affects only the number of wells designated in the computations described below; energy requirements per well are independent of the number of wells (since well interference is neglected and pumping efficiency is assumed constant), consequently small variations in pumping capacity will have a small impact on total cost of utilizing aquifer storage.

Results

Costs of various elements of a cyclic storage system were estimated for a 40 year project life as used throughout the study. For the mixes of surface storage and pumping capacity indentified which met the 95/95 criterion, elemental costs were estimated using three discount rates, 8, 12, and 18 per cent. Where future costs are included (e.g., OMR), costs are discounted to total present worth, so the discount rates do not include inflationary effects; rather changing prices are implicitly accounted for by taking time streams of costs, where applicable, in constant present dollars. To allow determination of aquifer management costs, it was necessary to specify a particular mean annual reservoir inflow. The value used was 300,000 AF/yr, which would be sufficient to irrigate a modest (e.g., on the order of 40,000 acres) agricultural area in a semi-arid climate. Specific elemental costs were estimated as follows:

a) Surface reservoir costs - computations were made using both $100 and $300/AF,

b) Surface reservoir OMR - $.05/AF/yr.

c) Pumping energy costs - both \$.02 and \$.12/KwH were used.

d) Pump purchase and installation cost - \$30,000.

e) Well drilling and casing - \$50/ft.

In addition, it is necessary to specify an aquifer depth for estimation of pumping costs. In this case, 300 feet was used. In order to provide sufficient submerged screen area to provide for pumping at maximum capacity with the aquifer near maximum drawdown, an additional 20 feet of well depth was assumed.

Results are shown in Tables 4.1a-e for surface storage sizes 0.4, 0.7, 1.0, 1.5 and 2.0 times mean reservoir inflow and associated pumping capacities. Where appropriate, costs are shown in present dollars. Figures 4.5 and 4.6 show selected results for discount rates of 8 and 18 per cent, respectively, each for pumping energy costs of \$.02 and \$.12/KwH. Note that the ordinate scale for aquifer costs is one-tenth that for surface and total costs. Clearly, the cost of surface storage far exceeds that of aquifer storage even at the smallest surface storage size considered. Also, Figs. 4.5 and 4.6 show results only for the low surface storage construction cost of \$100/AF; the trend is accentuated for higher surface costs. Further, increasing energy costs significantly only alters the total cost curve slightly.

The results make it clear that constraints on subsurface storage utilization are the key determinant in designing a cyclic storage system. Since it is desirable, at least under the range of parameters considered, to make the greatest possible use of aquifer storage to reduce the requirement for surface storage, aquifer size, taken here to be fixed, will be a very important variable. Pumping capacity as shown in Figs. 4.1 and 4.2 is important only until a level of roughly one-half of aquifer size (i.e., 50 per cent of the aquifer content can be pumped in one year) is reached; after that point the system is limited by aquifer size, rather than pumping capacity. Also, the system cost

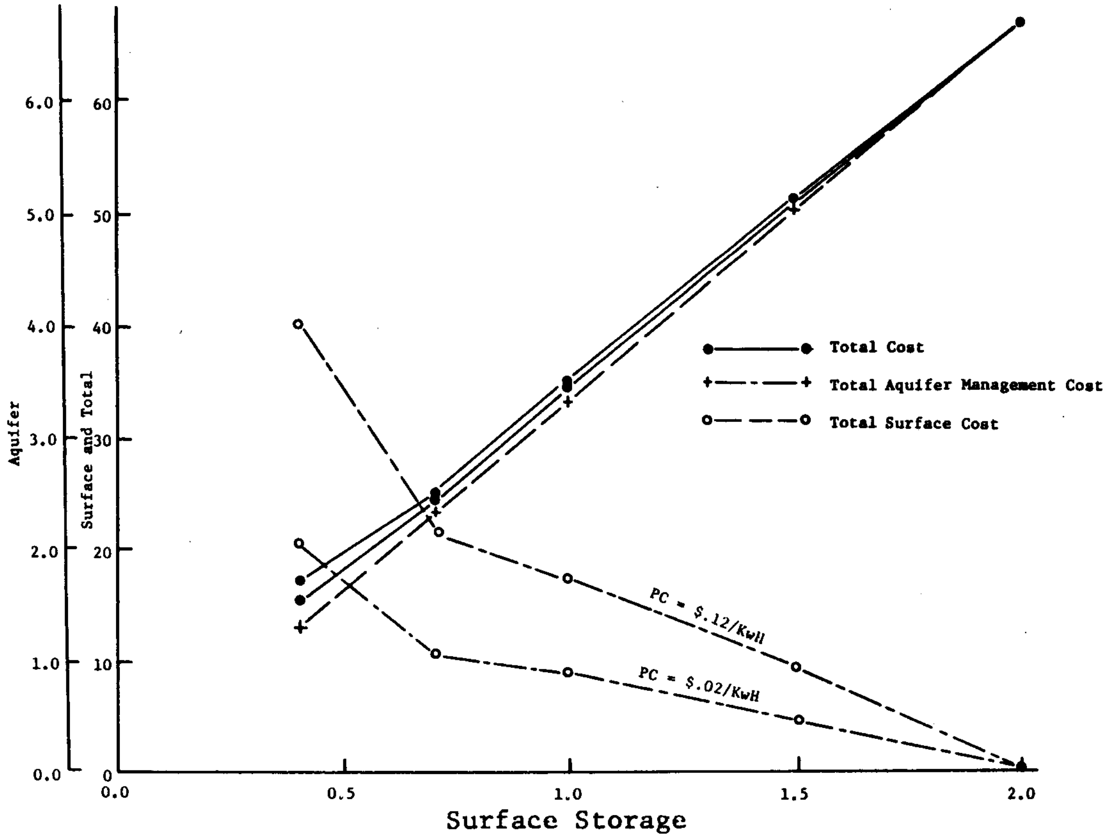


Figure 4.5 System Cost for Cyclic Storage Systems with Equal Performance for 18% Discount Rate

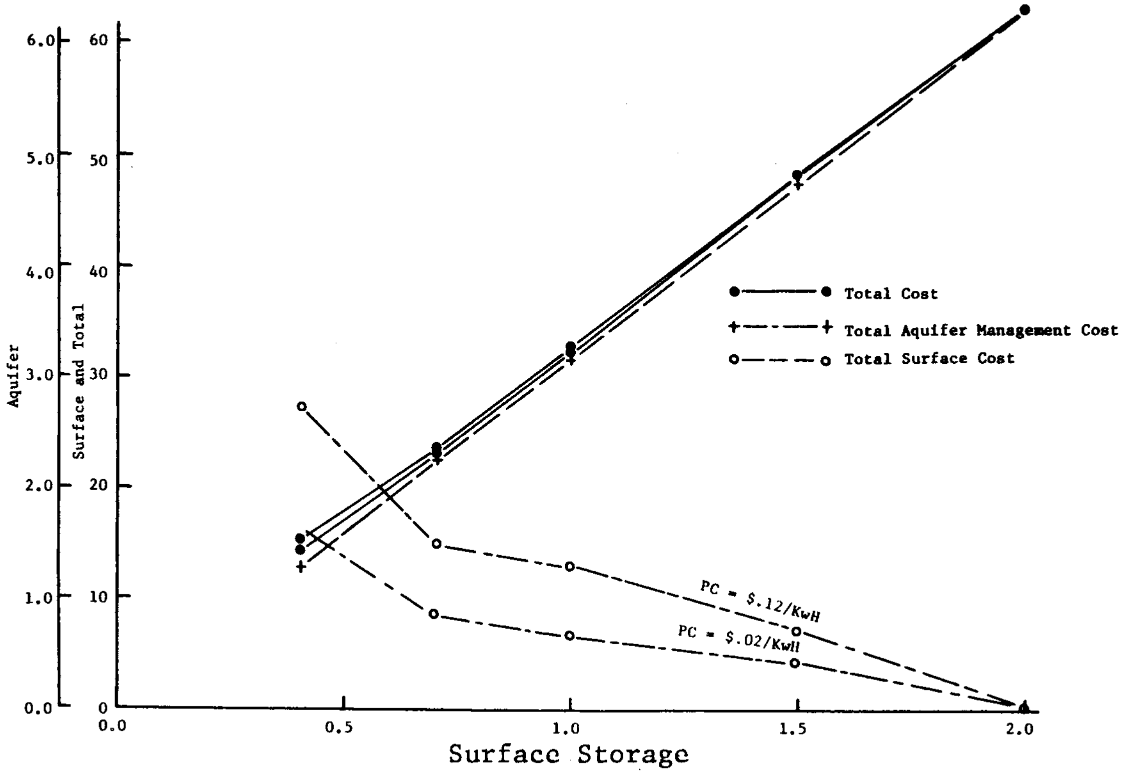


Figure 4.6 System Cost for Cyclic Storage System with Equal Performance for 8% Discount Rate

is most sensitive to the reliability level selected. Relaxing the reliability level somewhat while maintaining the same pumping capacity allows use of smaller surface storage, at substantially reduced total cost. These restrictions also suggest areas where more detailed modeling efforts are required, such as establishment of infiltration capacity and legal and institutional considerations which might limit management of aquifer storage in the manner specified here. These considerations are discussed in more detail in Chapter 5.

Table 4.1a Results of Cost Analysis for Surface Storage Size 0.4

DR Percent	PC $/KwH	CC $/AF	Cost: Millions of Dollars						
			RC	ROMR	WC	WP	TS	TAF	T
8	.02	100	12	1.43	1.67	.39	13.43	2.06	15.49
8	.12	100	12	1.43	1.67	2.35	13.43	4.02	17.45
8	.02	300	36	1.43	1.67	.39	37.42	2.06	39.48
8	.12	300	36	1.43	1.67	2.35	37.42	4.02	41.44
12	.02	100	12	.99	1.53	.29	12.99	1.82	14.76
12	.12	100	12	.99	1.53	1.77	12.99	3.30	16.29
12	.02	300	36	.99	1.53	.29	36.99	1.82	38.81
12	.12	300	36	.99	1.53	1.77	36.99	3.30	40.29
18	.02	100	12	.67	1.42	.22	12.67	1.64	14.31
18	.12	100	12	.67	1.42	1.32	12.67	2.74	15.41
18	.02	300	36	.67	1.42	.22	36.67	1.64	38.31
18	.12	300	36	.67	1.42	1.32	36.67	2.74	39.41

DR = discount rate

PC = pumping energy cost

CC = surface reservoir unit capital cost

RC = surface reservoir capital cost

ROMR = present worth surface reservoir operation, maintenance, and repair over project life

WC = well drilling and equipment purchase and installation cost, including discounted maintenance

WP = estimated expected value of present worth of well pumping costs

TS = total present worth of surface storage costs

TAF = total present worth of aquifer

T = total present worth of system cost

Table 4.1b Results of Cost Analysis for Surface Storage Size 0.7

DR Percent	PC $/KwH	CC $/AF	Cost : Millions of Dollars						
			RC	ROMR	WC	WP	TS	TAF	T
8	.02	100	21	2.49	.85	.22	23.49	1.07	24.56
8	.12	100	21	2.49	.85	1.30	23.49	2.15	25.64
8	.02	300	63	2.49	.85	.22	65.49	1.07	66.56
8	.12	300	63	2.49	.85	1.30	65.49	2.15	67.64
12	.02	100	21	1.73	.76	.17	22.73	.93	23.66
12	.12	100	21	1.73	.76	1.01	22.73	1.77	24.50
12	.02	300	63	1.73	.76	.17	64.73	.93	65.66
12	.12	300	63	1.73	.76	1.01	64.73	1.77	66.50
18	.02	100	21	1.16	.72	.13	22.16	.85	23.01
18	.12	100	21	1.16	.72	.78	22.16	1.50	23.66
18	.02	300	63	1.16	.72	.13	64.16	.85	65.01
18	.12	300	63	1.16	.72	.78	64.16	1.50	65.66

DR = discount rate

PC = pumping energy cost

CC = surface reservoir unit capital cost

RC = surface reservoir capital cost

ROMR = present worth surface reservoir operation, maintenance, and repair over project life

WC = well drilling and equipment purchase and installation cost, including discounted maintenance

WP = estimated expected value of present worth of well pumping costs

TS = total present worth of surface storage costs

TAF = total present worth of aquifer

T = total present worth of system cost

Table 4-1c Results of Cost Analysis for Surface Storage Size 1.0

DR Percent	PC $/KwH	CC $/AF	Cost: Millions of Dollars						
			RC	ROMR	WC	WP	TS	TAF	T
8	.02	100	30	3.56	.74	.17	33.56	.91	34.47
8	.12	100	30	3.56	.74	1.00	33.56	1.74	35.30
8	.02	300	90	3.56	.74	.17	93.56	.91	94.47
8	.12	300	90	3.56	.74	1.00	93.56	1.74	95.30
12	.02	100	30	2.47	.67	.14	32.47	.81	33.28
12	.12	100	30	2.47	.67	.81	32.47	1.48	33.95
12	.02	300	90	2.47	.67	.14	92.47	.81	94.28
12	.12	300	90	2.47	.67	.81	92.47	1.48	93.95
18	.02	100	30	1.66	.63	.11	31.66	.74	32.40
18	.12	100	30	1.66	.63	.64	31.66	1.27	32.93
18	.02	300	90	1.66	.63	.11	91.66	.74	92.40
18	.12	300	90	1.66	.63	.64	91.66	1.27	92.93

DR = discount rate

PC = pumping energy cost

CC = surface reservoir unit capital cost

RC = surface reservoir capital cost

ROMR = present worth surface reservoir operation, maintenance, and repair over project life

WC = well drilling and equipment purchase and installation cost, including discounted maintenance

WP = estimated expected value of present worth of well pumping costs

TS = total present worth of surface storage costs

TAF = total present worth of aquifer

T = total present worth of system cost

Table 4.1d Results of Cost Analysis for Surface Storage Size 1.5

			Cost: Millions of Dollars						
DR Percent	PC $/KwH	CC $/AF	RC	ROMR	WC	WP	TS	TAF	T
8	.02	100	45	5.34	.41	.095	50.34	.51	50.85
8	.12	100	45	5.34	.41	.57	50.34	.98	51.32
8	.02	300	135	5.34	.41	.095	140.34	.51	140.85
8	.12	300	135	5.34	.41	.57	140.34	.98	141.32
12	.02	100	45	3.70	.38	.077	48.70	.46	49.16
12	.12	100	45	3.70	.38	.47	48.70	.85	49.55
12	.02	300	135	3.70	.38	.077	138.70	.46	139.16
12	.12	300	135	3.70	.38	.47	138.70	.85	139.55
18	.02	100	45	2.50	.36	.062	47.50	.42	48.18
18	.12	100	45	2.50	.36	.37	47.50	.73	48.23
18	.02	300	135	2.50	.36	.062	137.49	.42	137.91
18	.12	300	135	2.50	.36	.37	137.49	.73	138.22

DR = discount rate

PC = pumping energy cost

CC = surface reservoir unit capital cost

RC = surface reservoir capital cost

ROMR = present worth surface reservoir operation, maintenance, and repair over project life

WC = well drilling and equipment purchase and installation cost, including discounted maintenance

WP = estimated expected value of present worth of well pumping costs

TS = total present worth of surface storage costs

TAF = total present worth of aquifer

T = total present worth of system cost

Table 4.1e Results of Cost Analysis for Surface Storage Size 2.0

DR Percent	PC $/KwH	CC $/AF	Cost: Millions of Dollars RC	ROMR	WC	WP	TS	TAF	T
8	.02	100	60	7.13	0	0	67.13	0	67.13
8	.12	100	60	7.13	0	0	67.13	0	67.13
8	.02	300	180	7.13	0	0	187.13	0	187.13
8	.12	300	180	7.13	0	0	187.13	0	187.13
12	.02	100	60	4.94	0	0	64.94	0	64.94
12	.12	100	60	4.94	0	0	64.94	0	64.94
12	.02	300	180	4.94	0	0	184.94	0	184.94
12	.12	300	180	4.94	0	0	184.94	0	184.94
18	.02	100	60	3.32	0	0	63.32	0	63.32
18	.12	100	60	3.32	0	0	63.32	0	63.32
18	.02	300	180	3.32	0	0	183.32	0	183.32
18	.12	300	180	3.32	0	0	183.32	0	183.32

DR = discount rate

PC = pumping energy cost

CC = surface reservoir unit capital cost

RC = surface reservoir capital cost

ROMR = present worth surface reservoir operation, maintenance, and repair over project life

WC = well drilling and equipment purchase and installation cost, including discounted maintenance

WP = estimated expected value of present worth of well pumping costs

TS = total present worth of surface storage costs

TAF = total present worth of aquifer

T = total present worth of system cost

Chapter 5

CONCLUSIONS

We have explored a simplified model of a cyclic storage system designed to deliver as reliably as possible a uniform annual demand. The ability of the modeled system to deliver the fixed demand was influenced by the streamflow statistical population, surface storage size, aquifer storage size, and aquifer pumping and recharge capacities. System performance would also be affected by the initial aquifer and surface reservoir storages which we chose to hold constant. System performance was summarized by the probability of meeting demand fully and the probability of always meeting at least 80% of the demand for each year of the project life. Also examined were the probability distributions of pumping requirements, as well as a number of secondary performance measures such as the distribution of surface reservoir storage, duration of supply shortfalls, etc.

For the systems examined, recharge and pumping capacities were set to relatively large values, so system performance was largely governed by total storage capacity, i.e., the sum of surface and aquifer storage. Although the pumping and aquifer storage statistics indicate that aquifer storage was near capacity throughout most of the simulated records, the few times when it was drawn down provided buffering against droughts which otherwise would have resulted in system failure. This is so because the operating rule used drew water first from surface storage; any remaining deficit between supply and demand was made up from the aquifer. The effective storage provided by the aquifer (as compared with an equivalent volume of surface storage) will decrease as pumping and recharge capacities are reduced. As a very rough rule, however, the effect of pumping and recharge limitations does not bear substantially on effective aquifer storage until either is reduced below about one-half of the annual system demand.

The effect of alternate streamflow populations on system performance was similar to that observed in previous studies of surface reservoir performance; specifically, reliability is impaired somewhat by increased variability of the marginal probability distribution of streamflows, and very substantially by long term streamflow persistence. It should be noted that even when combinations of demand and supply were such that system reliability was relatively high, e.g., 95-98%, the cyclic storage system was much less robust in its ability to supply demand when the streamflow population included long term persistence. For such situations, although the probability of failure was small, failures, when occurring, were quite severe. Similar failure severity is found in systems incorporating surface storage alone; it is not peculiar to cyclic storage systems.

A preliminary economic analysis was undertaken for a set of cyclic storage systems in which the streamflow population and all characteristics of the physical systems were fixed, with the exception of surface storage capacity and pumping capacity. A search was conducted for combinations of pumping capacity and surface storage yielding the same overall system reliability. It was found that the reliability measure used, i.e., the probability of <u>any</u> system failure occurring during the project life was too severe to yield practicably feasible storage sizes for an annual demand of 70% of the mean annual streamflow. Instead, an alternate measure was used which reflected the severeity of shortfalls which could be expected with a given probability. Insofar as the aquifer storage capacity was fixed, it was found that system reliability was insensitive to pumping capacity when surface storage was reduced below a critical level, i.e., no pumping level could be found to allow the system to attain the desired reliability. For larger surface storage capacities, however, surface storage and pumping capacity could be traded off effectively.

When total system cost was estimated, it was found that the discounted total cost of surface storage far exceeded that of aquifer management for all pumping capacity-surface storage combinations considered. This indicates that future work should consider the cost of supply shortfalls, rather than taking system reliability as a rigid constraint. The results also suggest that the conceptual approach to system management hypothesized here, specifically to use aquifer storage as a secondary buffering mechanism to make up shortfalls in release from the surface reservoir, might be reversed to consider aquifer storage as the primary buffering mechanism with surface storage used only in the event of shortfalls in aquifer storage. For the simple system considered, this philosophical reversal would make little difference because, once a surface reservoir of a given size has been constructed, the capital cost and a substantial portion of OMR may be considered as a sunk cost which must be paid regardless of the release policy. Consequently, the delivery cost of surface water may be less than ground water pumping costs. If a multiple purpose reservoir were considered, however, particularly if hydropower generation were an alternate use of water and, as in the Northwestern U.S., if releases for hydropower were mostly highly valued during the winter months, a substantially different operating policy from that used here might be preferred. This also emphasizes the necessity to consider a seasonal, rather than annual time scale in subsequent studies.

While we do not wish to diminish the significance of the results of this study, we emphasize the preliminary nature of the investigation, and it is important to point out directions that future work might most profitably take, and limitations on the cyclic storage concept in general. With respect to the latter, the number of factors influencing system performance is so large that it is necessary to investigate a real system, rather than a family of hypothetical systems as was done here. In doing this, we would forego the ability to generalize results; however, in the absence of a closed form solution describing system performance as a function of the factors investigated here, the hope for which seems remote, the combinatorial problem in extending the present analyses, while retaining the family of systems investigated here, would become overwhelming. Consideration of a specific system, or a few such systems, would allow the following problems to be addressed:

1) A seasonal time scale should be used to reflect the phasing of system demand and the availability of excess releases for recharge. This would also allow a realistic appraisal of the potential limitations on pumping and recharge.

2) The dynamics of surface-stream interactions, as well as the effects of natural recharge should be considered.

3) The constraints imposed by distribution system capacity in limiting surface-aquifer storage interaction should be investigated.

4) Depending on the level of pumping required and aquifer transmissivity, well interactions may alter pumping costs and may provide a variable constraint on pumping capacity. Such interactions should be considered,if appropriate.

5) Specific schemes for effecting artificial recharge should be reviewed. Depending on soil characteristics, surface application may or may not be feasible. If injection is necessary, the associated costs must be modeled. It is most important to determine feasible recharge rates. For many systems, this may be the controlling variable for use of cyclic storage.

In addition to these site-specific problems, the constraints provided by existing institutional arrangements cannot be ignored. One reason for the predominant emphasis on development of surface water in the U.S. has been that the control of impounded water is usually well defined. In the case of aquifer storage, however, control is fragmented. In some states no permit whatever is required for drilling a well, and in many others even very large wells are unmetered. This, of course, limits the potential for cyclic storage, since water held in subsurface storage is effectively regarded as a free good to pumpers (disregarding pumping costs, which represent the cost of access). There can be little incentive to recharge an aquifer artificially if ownership of the stored water cannot be retained. Gleason (1976) has reviewed this issue under California Water Law, and found that certain rights to recharged water can be retained. Similarly, a promising alternative to provide some incentive for more efficient management of aquifer storage is water banking, as examined by Angelides and Bardach (1978). In any event, it is difficult to imagine operation of aquifer storage in the same manner as a surface reservoir even in the best case where pumping is metered and water exchanges are possible if withdrawal capacity is fragmented. The conceptual solution to the problem is a regional authority, such as an irrigation district which would hold title to all pumping rights. Most analytical work to date has assumed that a basin-wide authority makes water allocation decisions. (Maddock (1974) used this approach and pointed out some of the obvious limitations of this assumption. Maknoon and Burges (1978) have examined the issue of a regional authority and found it to be, in most situations, impracticable. The largest single issue in aquifer management involves development of cohesive management. It is necessary for research workers to explore what might be done in the absence of existing institutional constraints and to explore management possibilities for different institutional arrangements.

In concluding, we view the primary contribution of the present work as the demonstration of the potential for cyclic storage. The limitations discussed here indicate that the model results represent an upper bound on the effectiveness of aquifer storage in augmenting surface storage. It is important to emphasize, however, that the discounted cost of managing a given unit of aquifer storage is approximately an order of magnitude less than providing the same unit of surface storage; even with the acknowledged limitations, there are more than adequate reasons to pursue the suggested extensions of our analysis.

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