Cyclic Storage: A Preliminary Assessment

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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 is investigated on an annual scale to provide insight into the most important physical and climatic (streamflow) parameters governing cyclic storage performance. The hypothetical system is fully characterized by aquifer capacity, pumping and recharge capacity, surface storage size, annual demand, and reservoir inflow statistics, including annual mean, coefficient of variation, skew coefficient, lag one correlation coefficient, and Hurst coefficient. System performance under a range of these parameters is reviewed via Monte Carlo simulation; for the cases considered system performance is almost always limited by total system storage (sum of surface and aquifer storage). A preliminary economic analysis indicates that the cost of providing flow buffering via development of subsurface storage is about an order of magnitude less than for surface storage in the cases considered.

INTRODUCTION

Since the time of Joseph, man has recognized the importance of smoothing the effects of climatic variability on his well-being, particularly in the most basic activities such as food production. The earliest attempts to mitigate the effects of climatic variability were through storage of excess food from plentiful years for consumption in less benign periods. More recently in man's history it has been recognized that storage of water, rather than food can enable maintenance of high production levels with much less sensitivity to climatic variability. Storage of water also has the benefit that seasonal variations in the hydrologic regime, which are especially important in arid and semiarid climates, can be smoothed out enabling use of winter and spring runoff for irrigation during the growing season. It was this idea that motivated the large reclamation projects of the western U.S.

The desirability of providing streamflow buffering, both for reduction or elimination of drought effects and for altering seasonal runoff patterns has led to construction of surface impoundments. In recent years, however, it has become much more difficult to provide surface storage as a result of environmental restrictions, rapidly increasing construction costs, and construction difficulties associated with remaining sites.

Cyclic ground-water storage represents an alternative which can reduce or eliminate the necessity for surface storage. Cyclic storage refers to the use of an aquifer as a natural storage facility, from which water may be withdrawn in years or seasons of low natural runoff and to which excess runoff may be recharged. Such a system may be operated in conjunction with a surface reservoir, which offers possibilities for increasing system reliability (frequence with which nominal demands are met) or, for the same reliability, reducing the size of required surface storage.

The research community has given little attention to cyclic storage in favor of the related problem of conjunctive use. Although the division between these topics is not always clear, cyclic storage may be considered to refer to design and

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management of surface/subsurface storage systems with emphasis on long-term performance (e.g., resistance to droughts), while conjunctive use emphasizes the mechanics of stream-aquifer interactions and related management strategies or operating policies which exploit synergisms between streamflow and ground-water gradients for such objectives as maximizing reliability or net benefits of operation of a surface reservoir and ground-water pumping facilities.

Notable work in the conjunctive-use field includes papers by Buras and Hall (1961), Dracup (1966), Maddock (1974), and Coskunoglu and Shetty (1981). The distinguishing feature of these efforts is use of optimization techniques to determine reservoir release and ground-water pumping strategies to meet an array of instream flow requirements and external demands. Although general in concept, the conjunctive-use work is sufficiently detailed to preclude exploration of wide ranges of physical systems (although some of the techniques may be well suited for examination of, for instance, expansion alternatives for a specific system). From a practical standpoint, therefore, the conjunctive-use demonstrations have been specific to the physical and management characteristics of a few particular systems.

In this work, a somewhat different approach is taken which makes use of synthetic streamflow generating techniques to drive a family of surface/subsurface systems characterized by the structure of the surface inflows, surface and subsurface storage capacities, water demand, and certain other physical and management parameters. To accomplish this, a highly simplified management model is used, which allows consideration of system reliability and cost for a wide range of members of the system family. Therefore, this work should help in placing the previous work into a broad context, which brackets the range of many real systems.

Two characteristics of a family of cyclic storage systems are investigated. The first is the physical reliability of each system in meeting a fixed demand, where several reliability measures are used (all are related to probabilities of physical system failure, e.g., inability to meet demand). The second is the total discounted system cost, and its apportionment to the surface and aquifer components of the system.

The potential for use of cyclic storage has been described elsewhere (e.g., Thomas, 1978; Ambroggi, 1978), and it is not our purpose to advocate such systems, but rather to delineate the conditions under which they may be beneficial. It is worth noting, however, that there are few if any instances where cyclic storage is being used currently on a large scale; for a variety of reasons existing dynamic storage is provided almost entirely in the form of surface impoundments, in spite of the fact that subsurface storage potential far exceeds that of surface facilities (Ambroggi, 1978). At present, however, subsurface storage is usually viewed as being limited by natural recharge, notwithstanding that in a number of important ground-water basins withdrawal exceeds natural recharge. While substantial efforts in recharge are made worldwide (United Nations, 1975), only a few situations exist where aquifer recharge is augmented artificially on a large scale (Long Island, New York is a notable example). It will become clear from the results given here that artificial recharge on a large scale (comparable to withdrawals from a surface reservoir) is the key element of cyclic storage which distinguishes it from the conjunctive use of surface and ground water as currently practiced.

SYSTEM MODEL

A simplified model of a hypothetical system is considered which enables investigation of the performance of a family of physical systems. The family includes a single surface stream which flows to an impoundment. The impoundment is operated to provide as uniform a withdrawal rate as possible to a downstream demand area (e.g., an irrigation project). The project is assumed to be underlain by an aquifer of finite storage capacity. When releases from the surface reservoir exceed system demand, the excess is artificially recharged to the aquifer subject to a constraint on the recharge capacity and the maximum aquifer storage. When surface releases are inadequate to meet demand, the difference between demand and surface release is made up by pumping from the aquifer. If the demand still cannot be met, the system has failed in the given time period, and the magnitude of the deficit is noted. The reliability indices computed (described below) include measures of both the frequency of failure and the magnitude of deficits when failure occurs, so it is possible to distinguish between severe and marginal failures.

In all the analyses conducted here, an annual time scale was used; hence the objective of the systems modeled is to provide protection against annual scale streamflow fluctuations only. Generally, this limits applicability of the results to systems having total storage capacity greater than the mean annual streamflow. This is the case for many streams in the interior of the western U.S.; for example, the Colorado River system has total surface storage of about five times the mean annual streamflow at Lee Ferry. Both the Central Valley project of California and the Columbia River systems have total surface storage on the order of one-half of the total annual runoff. However, total storage including aquifers exceeds mean annual runoff, so the results are potentially applicable to these systems as well. Smaller streams in humid and semihumid climates, on the other hand, generally have combined storage considerably less than mean annual flow, placing them outside the range of applicability of this work.

The physical systems considered are assumed to be comprised of a surface-water reservoir upstream from a demand area which overlays the aquifer system. A diversion canal conveys water from the reservoir to the demand area. The diversion canal is assumed to have sufficient capacity to convey recharge water to the aquifer while simultaneously supplying the irrigation water. Recharge is assumed to be possible by surface application, e.g., flooding. The system is operated to supply all the demand from the surface reservoir when possible; when the maximum reservoir release is insufficient to meet the nominal demand the reservoir release is augmented by pumping from ground water.

The surface reservoir operating policy is as follows: release equals (annual) demand if inflow plus previous storage is greater than the nominal demand and inflow plus previous storage less nominal demand is less than storage capacity. If inflow plus previous storage is less than nominal demand, release is equal to inflow plus previous storage (empty reservoir condition); if inflow plus previous storage less nominal demand exceeds storage capacity release is augmented by the excess (spill condition). Canal diversion is equal to reservoir release up to the maximum limit of nominal demand plus aquifer recharge capacity. Although a more realistic system with time-varying demand and minimum instream flow requirements could have been considered, the simplifications made result in no loss of generality; Burges and Linsley (1971) have shown that system performance under a time-varying demand can be represented as an equivalent constant demand, and minimum instream flows can be considered as part of the nominal demand.

The aquifer system is modeled as a single-storage reservoir parameterized only by its capacity. In the economic analyses, it is necessary to prescribe the depth of the aquifer as well, to enable computation of pumping heads. For the purpose of calculating heads, the pumping lift is taken to be directly proportional to the volume of water stored in the aquifer, which is determined by mass balance. This is equivalent to an assumption of no well interference, or high transmissivity. The importance of this assumption is, of course, dependent on the pumping capacity specified. In the physical performance analyses, it is not necessary to consider individual well capacity, but only the aggregate. For purposes of computing pumping costs, knowledge of individual well characteristics is required. This issue is discussed later in the paper.

The parameters required to specify the physical system as described are (1) surface storage capacity, (2) aquifer storage capacity, and (3) maximum annual pumping and recharge rates. No constraint on maximum reservoir release is considered, as this is not normally a limitation on annual scale operation.

It is also necessary to specify the initial surface reservoir and aquifer storages. Throughout this work, the initial values used were 20% of capacity for the surface reservoir and 100% of capacity for ground-water storage. These values were considered to be representative of conditions at the initiation of operation of a new system. They were fixed in the interest of holding the number of variables to be examined to a manageable level. Experience elsewhere with analyses of the type conducted here (e.g., Lettenmaier and Burges, 1978) suggests that the initial conditions have only a modest impact on system performance, particularly if reservoir inflows are not highly persistent. This is confirmed by results for Markovian streamflow persistence with modest autocorrelations (although the persistence structure of the streamflow models used is more complex) that steady-state storage transition probabilities are reached quite quickly regardless of initial conditions (Howard, 1960).

The strategy used in this study was to employ a stochastic analysis to determine the empirical probability distributions of various system performance measures such as demand satisfied, pumping required, and recharge affected. To perform such an analysis, it is necessary to have a method of generating synthetic streamflow sequences. The streamflow generator used was the ARMA-Markov model developed by Lettenmaier and Burges (1977). This model has the capability of synthesizing (annual) streamflow sequences that exhibit both long-term persistence, i.e., extreme and lengthy droughts and periods of excess flow, and short-term persistence, which might be attributed to subsurface carryover effects on an annual scale (note that such carryover is dependent on the properties of the basin upstream of the surface reservoir, which are assumed to be unrelated to the aquifer storage modeled for cyclic storage operation). The model can also simulate streamflows having either the normal or three-parameter log normal marginal probability distributions. The latter distribution is positively skewed, a property which is found in most historic streamflow sequences. The marginal probability distribution controls the variability of flows which may be observed in a given year, while the short- and long-term persistence structure control the sequencing of flows, i.e., the patterns in which flows occur.

The parameters used by the streamflow generation model are the mean, μ, which was arbitrarily set at 1.0 (this conveniently allows the physical parameters of the cyclic storage model to be expressed as a fraction of the mean annual streamflow); the coefficient of variation, C_V; the skewness coefficient, G; the lag one correlation coefficient, ρ; and the Hurst coefficient, H. The latter two are indices of short- and long-term persistence, respectively. The details of the streamflow generation model are not at issue here; the interested reader unfamiliar with stochastic streamflow generation methods is referred to the excellent review paper by Lawrance and Kottegoda (1977) or to Lettenmaier and Burges (1977) for details of the particular model used here. The important point is that the model used is capable of generating synthetic sequences that are similar in a statistical sense to observed streamflow records.

Each cyclic storage system considered is fully specified by the physical system parameters and streamflow model parameters, the demand level, D (which since $\mu = 1.0$ is the ratio of annual demand to mean annual streamflow) and the initial storage of the surface reservoir and aquifer. For each (hypothetical) system investigated 500 streamflow sequences were generated, each of length 40 years. This sequence length was chosen as typical of project lifetimes often used in economic analyses. For each streamflow sequence generated, a number of performance indices were computed. The most important of these are:

a. The number of years in which the demand was met fully.

b. The number of years in which more than 80% of the demand was met.

c. The number of years in which withdrawals from the aquifer were required.

d. The number of years in which aquifer withdrawals exceeded 50% of capacity.

e. The number of years in which pumping equalled capacity.

These indices are sufficient to characterize the general performance of both the system as a whole and the aquifer subsystem.

RESULTS—PHYSICAL PERFORMANCE

The model was run for 500 independent sequences of length 40 years for each of 32 model configurations, where a model configuration is defined by a set of streamflow generation parameters, physical system parameters, and demand level. The four sets of streamflow generation parameters considered are given in Table 1(a), while Table 1(b) specifies the physical system parameters considered. Each combination of streamflow generation parameters and physical system parameters was implemented for two demand levels, D = 0.5 and 0.8. Taken together, these combinations represent all 32 configurations.

The results are summarized as empirical cumulative distribution functions (ECDF's) of each of the five indices over the 500 synthetic sequences generated for each system configuration. Figures 1(a) and 1(b) show the resulting ECDF's for streamflow population C, physical parameter set I, and demand 0.8. Figure 1(a) shows, for example, that the system described failed with probability about 2% in 20% or more of the project life (8 or more deficit years), or alternately that the demand was met in 32 years or less with probability about 98%. Likewise, less than 80% of the nominal demand could be delivered in 5 or more years with probability about 2% (98% probability of providing at least 80% of the nominal demand in 35 years or less). Also, at the same probability level pumping equalled capacity in three or more years of the project life (note that exceedance probability = 1 − cumulative probability) and some pumping was required in 13 or more years. Consequently, about one-half of the failures either could be averted or the magnitude of the resulting shortfalls reduced if additional pumping capacity were available. The remaining failures result from inadequate storage capacity, i.e., both the surface storage and aquifer storage being emptied. It should be noted that

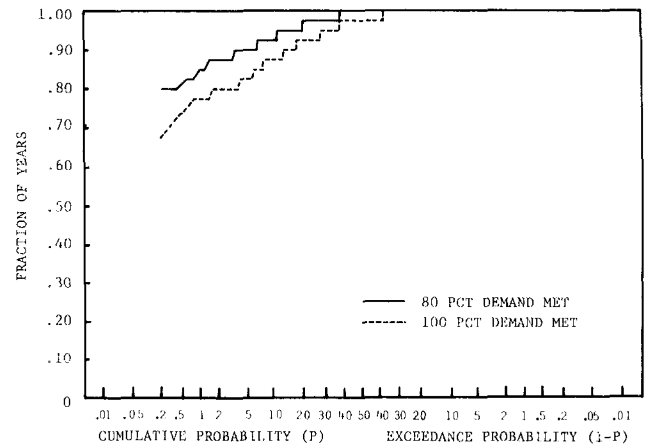

Fig. 1 (a). Empirical cumulative distribution function of number of periods demand satisfied, nominal demand D = 0.8, parameter set I, streamflow population C.

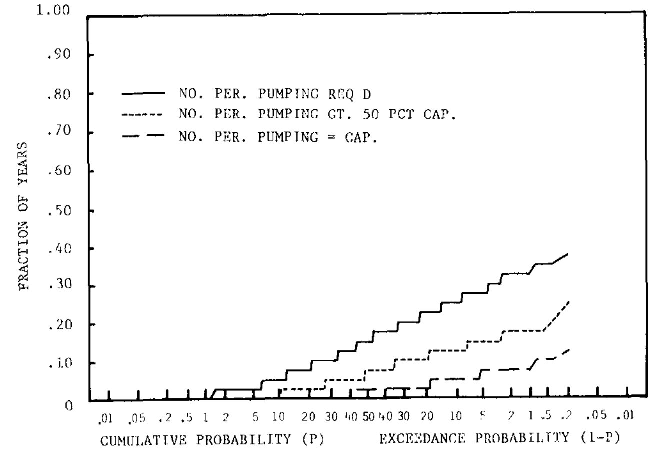

Fig. 1 (b). Empirical cumulative distribution function of pumping requirement, nominal demand D = 0.8, parameter set I, streamflow population C.

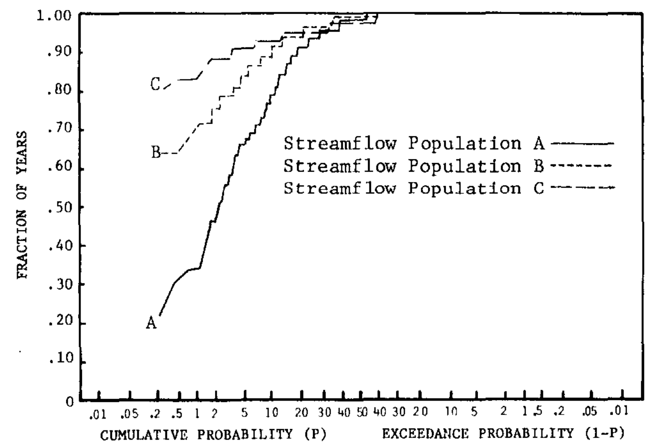

Fig. 2 (a). Empirical cumulative distribution function of number of periods demand fully satisfied, nominal demand D = 0.8, parameter set I.

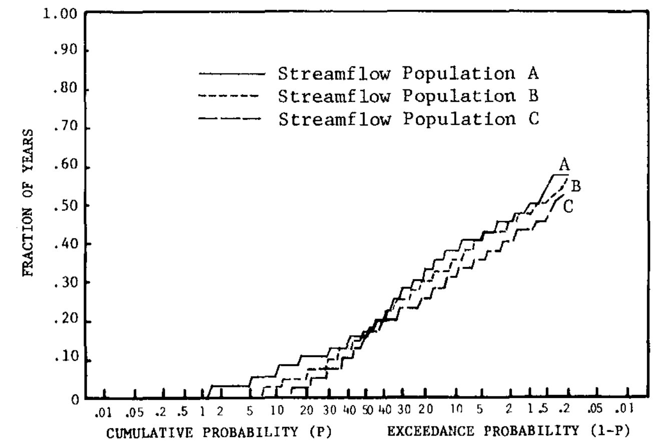

Fig. 2 (b). Empirical cumulative distribution function of number of periods pumping required, nominal demand D = 0.8, parameter set I.

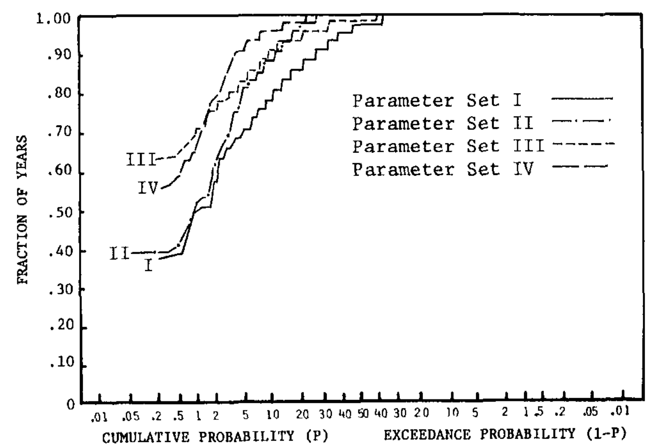

Fig. 3 (a). Empirical cumulative distribution function of number of periods demand fully satisfied, nominal demand D = 0.8, streamflow population B.

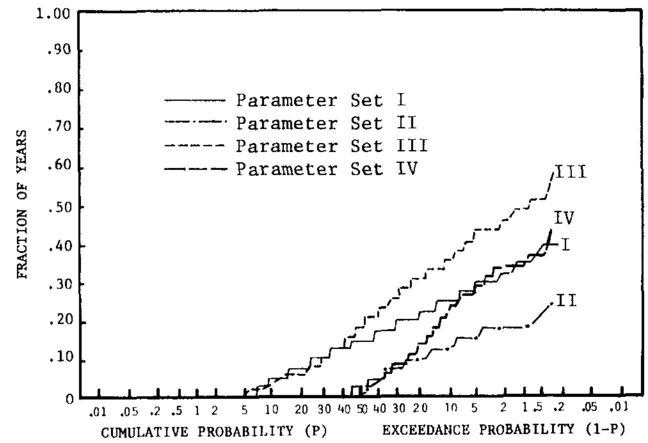

Fig. 3 (b). Empirical cumulative distribution function of number of periods pumping required, nominal demand D = 0.8, streamflow population B.

98% system reliability (2% failure rate) is a commonly accepted figure in the waterworks industry. This level is used here for illustrative purposes; for reasons discussed in the following section, however, this reliability level may be unreasonably high.

Similar results were obtained for all 32 system configurations. As a means of summarizing these results, the ECDF's of total supply and pumping, corresponding to the lower and upper curves in Figures 1 (a) and 1 (b), respectively, were plotted (a) for fixed physical system parameters and demand level, and the three streamflow populations A-C [Figures 2 (a) and 2 (b)], and (b) for fixed streamflow population and demand for the four sets of physical system parameters I-IV [Figures 3 (a) and 3 (b)]. In Figures 2 (a) and 2 (b) the physical system is specified by parameter set I [Table 1 (b)] while in Figures 3 (a) and 3 (b) the streamflow population is B [Table 1 (a)]; the general features of the results are the same, however, for the other physical systems and streamflow populations considered.

Figure 2 (a) shows that system reliability is affected as expected by the streamflow population; specifically, reliability is reduced as streamflow persistence and variability increase. It is interesting that the probability of no failure occurring (i.e., 100% of demand met for all years of the project life) is in the vicinity of 50%, apparently independent of the streamflow population parameters for populations A, B, and C. These populations all have the same coefficient of variation and skew coefficient, i.e., identical marginal probability distribution, which appears to control the failure probability. Population D, on the other hand, has smaller coefficient of variation and zero skew and shows reduced failure probability (here failure probability is defined as the probability that one or more shortfalls in supply will occur during the project life). For the streamflow populations with identical marginal distributions, the differences in system performance are associated with the steepness of the ECDF; i.e., for small cumulative probabilities (high exceedance probabilities), much more severe failures are encountered for the populations with high long-term persistence. This results from the relatively long droughts encountered with such streamflows, which leads to emptying of both the storage reservoirs and the aquifer.

The pumping ECDF's [Figure 3 (b)] do not display the same sensitivity to streamflow population parameters; the changes are somewhat more subtle. The primary difference is that the ECDF's become flatter as streamflow persistence is reduced, i.e., there is greater variability in the number of periods during which pumping is required. Although this may initially seem counterintuitive, it is attributable to the difference in the typical length of supply shortfalls from the surface reservoir. If one conducts an analysis of the so-called critical periods in operating a single surface reservoir (e.g., Burges and Lettenmaier, 1977) it is found that the number of critical periods is much lower if the streamflow regime is long-term persistent, whereas the length of critical periods is much longer. For short-term persistence models, the shorter critical periods tend to result more from isolated years of extremely low flow rather than from multiple years of deficient flow, with more

Table 1 (a). Streamflow Population Parameters

Set	*Hurst Coefficient, H*	*Lag One Correlation, ρ*	*Coefficient of Variation, C_v*	*Skew Coefficient, G*
A	0.8	0.4	0.5	1.0
B	0.7	0.2	0.5	1.0
C	0.5	0.2	0.5	1.0
D	0.5	0.2	0.25	1.0

Table 1 (b). Physical System Parameters

Set	*Surface Storage Capacity, S*	*Aquifer Storage Capacity, C*	*Maximum Annual Recharge Rate, I_{max}*	*Maximum Annual Pumping Rate, P_{max}*
I	0.5	1.0	1.0	0.4
II	2.0	1.0	1.0	0.4
III	0.5	3.0	1.0	0.4
IV	2.0	3.0	1.0	0.4

variability in the number and severity of failures. The mean number of years in which pumping is required (hence the number of critical periods) is about the same for all streamflow populations considered.

Further insight into system operation is gained by reviewing the ECDF's of supply and pumping for a fixed streamflow population under varied physical configurations. Figure 3(a) shows the sensitivity of supply delivered to system configuration. The results are generally as expected, i.e., the best reliability is provided by systems with the largest storage. It is worthy of note that system reliability for configuration IV is not much improved as compared with system III even though the latter has an additional 1½ units of surface storage. For both these systems, aquifer storage is quite large. On the other hand, where aquifer storage is smaller (systems I and II), addition of the same increment of surface storage has a relatively more beneficial effect on system performance. This appears to suggest that the marginal physical benefits of storage decrease with the level of storage provided, which of course must hold in the limit of very large storage as 100% reliability is approached.

The relationship of the ECDF's for pumping are again less clear. One can, however, justify the relative values of ECDF's for systems I and II, and III and IV; for both these sets the second system configuration contains more surface storage for the same aquifer storage, consequently less pumping should be required. The relationship between systems with identical surface storage (i.e., I and III; II and IV) is less clear; in both these cases the system with smaller aquifer storage is also pumped less frequently. This may be explained by joint consideration of total system reliability. The systems with less total storage usually are brought about by emptying of both surface and aquifer storage rather than the pumping limitation. When both storage zones are empty, a failure is recorded but no pumping is registered. On the other hand, the larger aquifer systems (C and D) are emptied less often, and rely on aquifer pumpage to meet demand during droughts when the smaller systems would have failed.

Similar results were reviewed for sensitivity of supply and pumping to streamflow populations for the other three system configurations, and alternately for sensitivity of supply and pumping to system configuration for the other three streamflow populations. Although there are some differences from the results selected for presentation here, the general features which are apparent in Figures 2 and 3 hold for these systems as well, and the above discussion remains qualitatively accurate.

To this point only physical measures of system performance have been considered. In a particular application, costs will vary greatly depending on the type of storage that is developed to meet a given reliability constraint. In the following sections, a preliminary economic analysis of alternative cyclic storage systems is presented.

ECONOMIC EVALUATION

In the previous section the physical performance of cyclic storage systems was analyzed over a range of streamflow populations, physical system parameters, and system demand. Usually, many of the parameters determining the system configurations evaluated are fixed; for instance, the designer has no control over the streamflow population and the system demand is usually given. Some of the physical parameters such as aquifer storage may be fixed as well. The problem the designer faces is to select a system that meets the demand subject to the given streamflow, demand, and physical system characteristics. A criterion often used in system selection is net economic benefits. If system reliability is fixed, however, variations in economic benefits between competing systems are attributable solely to system cost, which is usually much easier to quantify than net benefits. For the systems considered here, total discounted cost over the project lifetime of system construction and operation, maintenance, and repair is used as the discriminant.

To justify use of system cost as the measure of relative system worth, it is necessary to insure that all the systems considered perform identically. As noted above, aquifer capacity is usually fixed. Further, it is assumed here that recharge capacity is also fixed, although at a value large enough so that it does not normally constrain system operation. While this choice is made for convenience, sensitivity tests showed that as long as recharge capacity exceeded approximately one-half the system demand, performance was nearly independent of recharge capacity. This leaves surface storage capacity and pumping capacity as the physical system parameters to be varied. For the results reported here, annual demand was taken as 0.7 times the mean annual surface reservoir inflow, and streamflow population B was used. Surface storage capacities were then sequentially fixed at $S = 0.4, 0.7, 1.0, 1.5$, and 2.0, and corresponding sets at 500 simulations each made for a range of

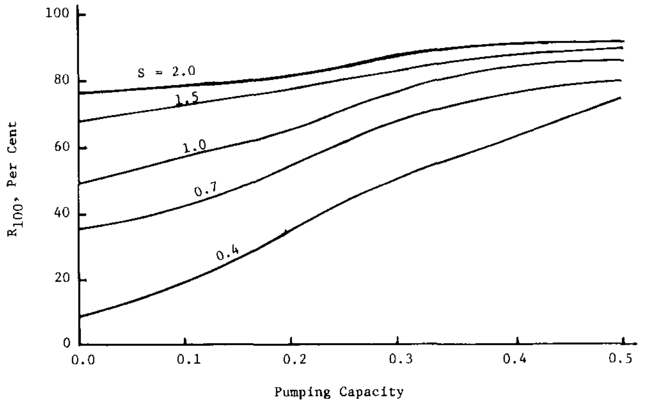

Fig. 4. R_{100}, probability of no failures occurring in 40-year project life as a function of pumping capacity and surface storage capacity, S_1, for streamflow population B. Demand = 0.7, recharge capacity = 1.0, aquifer storage capacity = 1.0.

pumping capacities. For each system configuration, system reliability was computed initially as the fraction of sequences for which demand was 100% satisfied (i.e., no system failures occurring throughout the 40-year project life). The resulting family of curves is plotted in Figure 4 where the numerical results have been smoothed appropriately to account for sampling variability.

It is immediately apparent from Figure 4 that none of the configurations tested are capable of meeting the 98% reliability requirement commonly used; in fact, an unrealistically large surface storage capacity would be required to meet such a reliability requirement. It is also clear that increasing pumping capacity with fixed surface storage ultimately results in diminishing incremental improvements in reliability; at this point the importance of pumping is subordinated to the limitation of storage capacity.

The inability of the systems tested to meet the commonly used 98% reliability level is a result of the manner in which reliability, R_p, is defined. Specifically, a p% reliable system satisfying the R_p reliability criterion is one which has a probability p that the nominal demand will be met in *all years* of the project life. This is a much more rigid requirement than an expected (100−p)% failure rate for any given streamflow sequence. Moreover, R_p makes no statement of the magnitude of shortfalls that might be encountered. Consequently, an alternative reliability measure, R_p^*, was defined such that the expected minimum supply delivered in p% of the project life in R_p^*% of the nominal demand. This measure incorporates both the applicable percentage of the project life and the associated severity of shortfalls. Although measures such as the expected, or average shortfall might have been used to quantify shortfall severity, the expected shortfall contains no information regarding the worst case, which is often used for planning.

A realistic criterion for equating system performance which is used here is $R_{95}^* = 95\%$, i.e., a reliability such that for at least 95% of the project life, the most severe shortfall is expected to result in delivery of no less than 95% of the nominal demand. This performance level is denoted as 95/95 hereafter.

Figure 5 shows the resulting R_{95}^* for the same range of surface storage/pumping capacity configurations plotted in Figure 4. It is clear that the 95/95 reliability criterion can be met for all of the surface storage capacities considered. For $S = 2.0$, R_{95}^* exceeds 95% of the nominal demand even for zero pumping capacity, so the configuration $S = 2.0$, $P_{max} = 0.0$ was used, recognizing that this system is slightly more reliable than the other four defined by the crossing of the 95/95 line with the S = constant curves.

Having defined five alternative systems with comparable performance, it remains to compute the cost of implementation of each system. This cost was broken into five components, (1) surface reservoir construction cost; (2) surface reservoir operation, maintenance, and repair (OMR) cost; (3) pumping energy cost; (4) pump purchase and installation cost; (5) pump maintenance cost; and (6) well drilling and casing cost. Table 2 summarizes the unit costs used in the analysis and their basis. These are defined in more detail by Lettenmaier and Burges (1979) wherein the analysis reported below is repeated for a range of elemental costs. However, while the specific total system costs

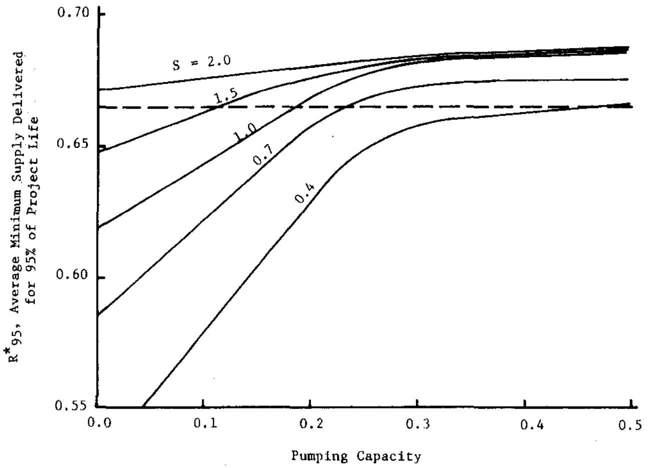

Fig. 5. R_{95}^*, average minimum supply delivered in 95% of project life as a function of pumping capacity and surface storage capacity, S_1, for streamflow population B. Demand = 0.7, recharge capacity = 1.0, aquifer capacity = 1.0.

Table 2. Elemental Cost Estimates for Cyclic Storage Systems, Project Life = 40 Years

Cost Element	*Unit Cost*	*Computation Basis*
Surface storage construction	$ 100/AF	Maass, *et al.*, (1962) as adjusted.
Surface reservoir OMR	.05/AF/yr	Maass, *et al.*, (1962) as adjusted.
Well drilling	50/ft	16-in. casing, 320-ft depth.
Pump purchase and installation	30,000/unit	Lettenmaier and Burges (1979).
Pump maintenance	66/yr	4-yr overhaul cycle, 20-yr replacement cycle.
Pumping energy	.02-.12/KwH	Linear drawdown (no well interference).

vary as elemental unit costs are perturbed, the general characteristics found in the case considered here do not, and the single set of elemental costs specified is sufficient to illustrate gross relationships.

Well depth was based on a 300-foot deep aquifer with an additional 20 feet to allow sufficient screen area to meet the nominal withdrawal rate with the aquifer near maximum drawdown. The capacity of each well was based on a 16-inch diameter casing with a 300-HP pump operating at 80% efficiency, capable of delivering 3000 gpm. For each year, the power cost was computed on the basis of the average head during that year. Pump purchase and installation cost is typical of experience in the Yakima Valley, Washington. Two unit energy costs were considered. The low value ($.02/KwH) is typical of the delivered cost of hydropower in the Pacific Northwest, while the higher value represents the cost of new thermally generated power. All costs are in present dollars, with appropriate discounting at an 8% rate. This rate is within the range of current market interest rates corrected for inflation.

The results of the economic analysis are shown in Figure 6. Initially, it was expected that the total cost would have a "U" shape; however, for all combinations of elemental costs considered, minimum total cost was achieved when surface storage was the minimum that allowed the reliability requirement to be met. The reason for this is apparent when one considers that total aquifer management cost (i.e., pumping cost, well drilling, pump purchase, installation, and maintenance) is roughly an order of magnitude smaller than surface storage construction and discounted OMR. Although certain costs have been neglected (i.e., system components necessary to effect artificial recharge), the costs neglected are unlikely to affect the gross nature of the estimated system costs.

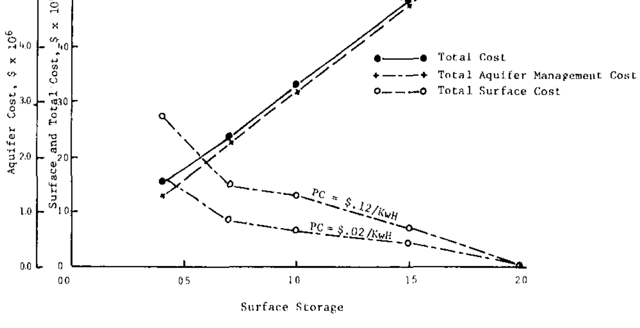

Fig. 6. Total, surface and aquifer cost as a function of surface storage capacity for surface storage/pumping capacity combinations defined by Figure 5.

SUMMARY AND CONCLUSIONS

For the systems examined, recharge and pumping capacities were set to relatively large values, so system performance was governed largely 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 occurred 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 initially used, i.e., the probability of *any* 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 alternative measure was used which reflected the severity 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 cost of surface storage far exceeded that of aquifer management for all pumping capacity/surface storage combinations considered. This result is, of course, dependent on system objectives; for instance, for a multipurpose system where hydropower generation is an alternate use of stored water, different results would be achieved. Nevertheless, the differences in cost between the two sources are so large that these results can serve as a starting point for future analyses.

Therefore, the results presented here, although preliminary, do suggest 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 extensions to the work would probably necessitate investigation of a single real system, rather than a family of hypothetical systems as was done here. In doing this, the ability to generalize results would be foregone. 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 otherwise would become overwhelming. Consideration of a specific system, or a few such systems, might allow the following problems to be addressed:

1. Seasonal distribution of supply and demand.

2. Dynamic effects of surface-stream interactions, as well as natural recharge should be considered.

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

4. Well interactions, which may alter pumping costs and may provide a variable constraint on pumping capacity.

5. Specific schemes for effecting artificial recharge, including the feasibility of surface application and injection modeled.

In addition to these site-specific problems, the constraints provided by existing institutional arrangements cannot be ignored. 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. Probably the largest single issue in aquifer management involves development of cohesive management (Maknoon and Burges, 1978). It is necessary for researchers to explore the potential for implementation of cyclic storage both within and without the confines of existing institutional constraints.

The primary contribution of the present work is the demonstration of the potential for cyclic storage. The limitations discussed here indicate that the model results may 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.

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