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SUBJECT: Methods for Storage/Yield Analysis

CATEGORY: Guidance

1. **References**:

a. Cole, 1995. "CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 2.0," Instruction Report EL-95- 1, Cole, T.M., and Buchak, E.M., 1995. USACE, Waterways Experiment Station, Vicksburg, MS. https://pdxscholar.library.pdx.edu/cengin_fac/130/

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2. **Purpose.** This Engineering and Construction Bulletin (ECB) provides technical guidance on theories, methods and application of reservoir water supply storage/yield analysis.

3. **Background.** The research about reservoir yield analysis methods outlined in this ECB was performed under the Flood and Coastal Storm Damage Research (FCSDR) and Development (R&D) program within USACE. The goal of the research was to both determine reservoir storage requirements to meet given demands, and to develop storage/yield relationships for reservoirs, shared reservoir pools, and reservoir systems. Storage/yield theory describes the need to store water for future use to supply a consistent demand for water, hydropower, water quality,

or other purposes. Traditional methods define a storage requirement as the maximum cumulative deficit between streamflow and demand over a period of record. Various other methods for storage/yield analysis are used to determine firm yield for an existing reservoir Conservation Pool, and also for an array of other storage volumes that produce more (or less) firm yield with more (or less) storage capacity. The storage/yield relationship generated by this process is straightforward for a constant release rate and a constant reservoir storage capacity, but more complex for reservoir operation schemes with seasonally varying storage levels or seasonally varying demands. An iterative simulation approach is the most effective method, as it can incorporate such operational complexities. The same storage/yield methods may also be used to determine the firm yield of some portion of a shared reservoir Conservation Pool, which differs from the previous analysis only in that the portion of the reservoir only receives a portion of the inflow.

4. **Discussion.** Various methods for storage/yield analysis were considered for determining the reservoir storage requirement to meet specified demands (or, identically, for determining the firm yield of a specified reservoir storage volume), and to develop full storage/yield relationships for reservoirs, shared portions of reservoirs, and reservoir systems. From that review of methods, the method of iterative simulation was chosen as the one method for use within USACE for estimating the storage needed to supply a water demand. This is the required method unless otherwise justified. The criteria for this choice was established by the aforementioned R&D program which directed that the methodologies focus on typical USACE water supply agreements, in which a water user repays the Government for the costs associated with a percentage of available reservoir storage space, in return for the right to make use of that storage volume. The focus on agreements centered on determining the volume of storage required within an existing multi-purpose, shared reservoir to supply a specified demand.

5. **Guidance.** This technical guidance is to be utilized when evaluating the allocation of water supply storage at USACE reservoir projects through methods for storage/yield analysis. This ECB does not provide guidance for storage accounting or other reservoir operation, nor mandate changes to the operation and management of any USACE reservoir project, and does not determine legal rights or obligations.

6. **Update.** This guidance and any new methods will be incorporated into the next appropriate policy document.

7. **Point of Contact.** The point of contact for this ECB is Mr. Sean L. Smith, P.E., Principal Hydrologic and Hydraulic Engineer, USACE Headquarters, CECW-EC, (202) 761-0301, email: sean.l.smith@usace.army.mil.

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PETER L. STURDIVANT, P.E.
Chief, Engineering and Construction
U.S. Army Corps of Engineers

Encl.
Appendix A – Methods for Storage/Yield Analysis
Appendix B – Abbreviations
Appendix C – Glossary

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APPENDIX A

Methods for Storage/Yield Analysis

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

A-1. **Introduction**.

a. The research about reservoir yield analysis methods outlined in this document was done under the Flood and Coastal Storm Damage Research (FCSDR) and Development (R&D) program within U.S. Army Corps of Engineers (USACE). The goal of the research was to both determine reservoir storage requirements to meet given demands, and develop storage/yield relationships for reservoirs, shared reservoir pools, and reservoir systems. This research included a literature review, a summary of USACE practices, a description of various case studies, and a description of a computational tool that can be used to implement the methods mentioned herein, the Hydrologic Engineering Center's (HEC) Reservoir System Simulation (HEC-ResSim) software. The research and this guidance are not intended to adopt a particular water or storage accounting methodology once a storage need and firm yield are determined, but are intended to guide the determination of available storage (firm yield) to satisfy a need in a reservoir.

b. The concepts and computation of firm yield, starting from the definition and traditional computation methods, through sensitivities in the analysis and recommended adaptations, are described in this document. Paragraphs A-2 and A-3 cover the definition of firm yield and the need for yield analysis within USACE. Paragraph A-4 describes the theory of determining storage requirement for a given demand, or equivalently the firm yield from a given storage capacity, covering streamflow volume analysis and reservoir simulation approaches. Paragraph A-5 discusses the inputs needed for a yield analysis, paragraph A-6 evaluates the sensitivity of the analysis to computational time interval, and paragraph A-7 evaluates the sensitivity to reservoir-induced losses (evaporation) and gains (rain directly on the pool).

c. Paragraph A-8 describes the operation of a multi-purpose reservoir to provide firm yield for water supply as well as other reservoir purposes, detailing the interaction of complementary and conflicting uses. Paragraph A-9 introduces the determination of firm yield within a shared Conservation Pool and describes the use of storage accounting (keeping track of a users' stored water) to reserve water for future use of a particular demand. Paragraph A-10 discusses the reliability of estimated firm yield, and details methods for describing the uncertainty about estimated firm yield and/or storage requirement.

d. Paragraph A-11 moves to multi-reservoir systems, both series and parallel as well as jointly and separately operated reservoirs, and discusses the determination of system firm yield as well as firm yield per reservoir. Finally, paragraph A-12 addresses the evaluation of firm yield for various purposes, depending on their relative priority within the system operation, and how those priorities affect the firm yield computation and the result.

A-2. **Definition of Firm Yield**.

a. Terminology describing yield for water supply is quite varied. Multiple terms are used for a single concept, and sometimes the same term is used for more than one concept. Further, even a yield estimate that is conceptually the same might be estimated in a different way with different assumptions than another estimate that uses the same terminology. This section offers a definition of "firm yield" for the purpose of this document, but the reader is cautioned to always be sure to investigate the meaning and estimation method of any firm yield estimate they encounter.

b. In this document, "firm yield" is defined as the largest consistent flow rate (demand) that can be provided without fail throughout a period of record of streamflow. The ability to store water increases the firm yield by allowing water to be saved and used to meet demand when streamflow is less than demand. Diversion of the firm yield brings the stored water volume exactly to zero once during the period of record, during what is designated the critical period for that firm yield and storage capacity. Greater storage capacity can increase firm yield up to a maximum equal to the average annual flow. For a given record of streamflow, the relationship between storage capacity and resulting firm yield is the storage/yield curve. The terms "safe yield," "critical yield," "dependable yield," and "prime flow" are also often used for this definition, and any of these terms might also be used for an estimate that includes a factor of safety or buffer.

A-3. **Need for Storage/Yield Analysis**.

a. The relationship between storage and firm yield (the ability to consistently supply a demand) is first evaluated when determining the required storage capacity of a reservoir in the planning stage. Yield can be determined for various uses of water such as M&I (Municipal and Industrial) supply, irrigation, hydropower, or downstream flow augmentation. The traditional techniques to evaluate firm yield were approached as determining the storage requirement to supply a given water use.

b. The storage/yield relationship is reevaluated when developing reservoir operating policies, because the choices about when to store water for supply, when to release water for various purposes, and what space to reserve for flood protection, all impact the yield of the reservoir, and specifically define the trade-offs between yield for various purposes. More recently, local water users seeking to supply small demands from a USACE reservoir have sought agreements in which some portion of the reservoir storage volume is reserved for their use. The determination of the volume required for a single user in a shared Conservation Pool is similar to the storage/yield computation for the Conservation Pool as a whole, but differs because the inflow is shared (as is typically the case with USACE multipurpose reservoirs), with the user receiving only a portion of the total inflow. The evaluation of the shared pool is also impacted by other reservoir uses. The methods described herein address the storage/yield for a reservoir at a site, the yield of the existing Conservation Pool at a reservoir, and the storage requirement for a use needing a portion of the shared Conservation Pool.

A-4. **Storage/Yield Theory**.

a. The basis of the relationship between storage volume and firm yield is that streamflow is variable over time. To provide water for some continuous demand (flow rate) that is at times greater than streamflow, one must be able to store water when streamflow is greater than demand (surplus) to use when streamflow is less than demand (deficit). The question asked is how much storage capacity is needed on a given stream to supply a given consistent demand. The storage requirement is based on both the demand and the amount and variability of available streamflow.

If the region experiences a wet season and a dry season, and there is often shortage during the dry season, water is stored during the wet season (time of surplus) to supply during dry season (time of deficit), referred to as within-year storage as shown in each year of Figure A-1. If there are some drier years whose annual average flow is less than demand, over-year storage allows retention of surplus inflow during wet years to continue to meet the demand during dry years. Figure A-1 shows the surplus inflow in Years 1 and 2 stored to not only meet demand in the dry seasons but also meet the annual shortage in drier Years 3 and 4. Regardless of whether the need is for within-year or over-year storage, the interest is in the maximum cumulative shortfall between demand and supply, which defines the water storage capacity needed to meet the demand throughout the period of record. Dry periods requiring use of stored water will occur several times within the period of record, and the driest periods requiring the greatest stored volume are referred to as critical periods.

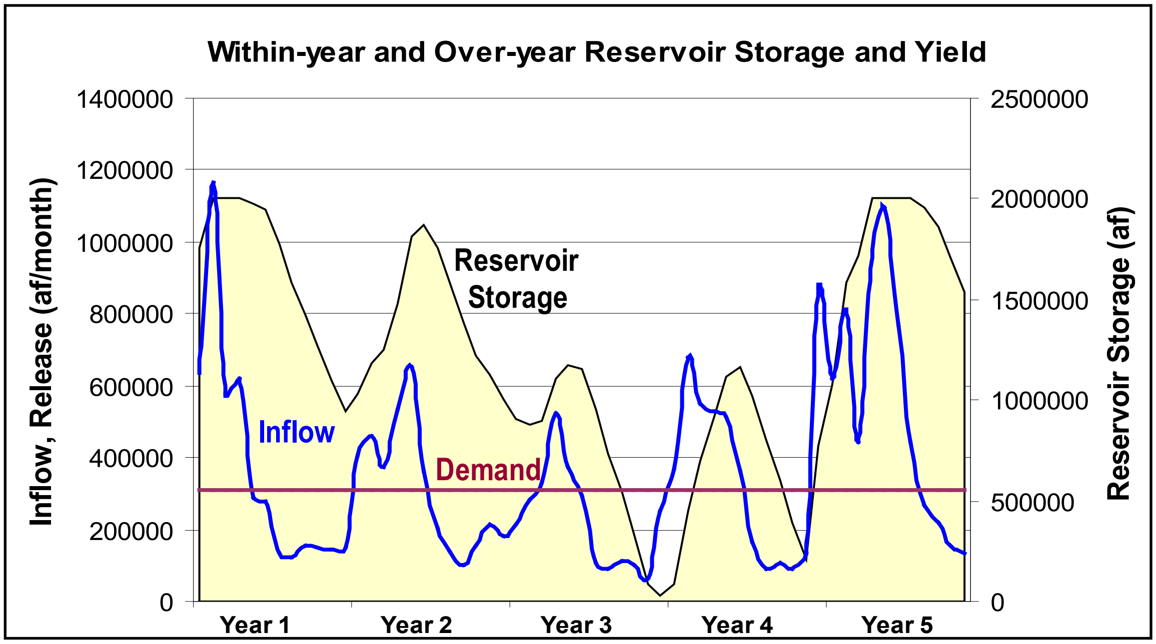

Figure A-1. Water storage for within-year deficit and over-year deficit.

b. Simple Methods.

(1) Traditionally, before modern computation capability, simple methods were employed to determine the storage/yield relationship for a site. The most common simple methods are the Rippl Mass Diagram and the Sequent Peak algorithm. These methods determine cumulative water deficit to define the storage requirement for a given consistent demand rate. The Rippl Mass Diagram is the least computationally intensive and is simply a graphical comparison of inflow accumulated over time to accumulated demand. Equation (A-1) shows accumulated inflow, and demand is accumulated in the same way.

$$Cumulative\_Inflow(t) = \sum_{i=1}^{i=t} Inflow(i) \quad \text{(A-1)}$$

(2) This approach is effectively restricted to evaluating a constant demand. For the inflow time-series shown in Figure A-2, a Rippl Mass Diagram is shown in Figure A-3, making note of two potential critical periods. The first period is very dry for a short period of time, and the second period is less dry, but for a longer period of time. Two different cumulative demands are also plotted, as floating lines with slope equal to demand. The demand lines are positioned at the beginning of the critical dry period (the point at which the cumulative inflow begins to flatten, showing inflow accumulating more slowly) to determine the greatest difference between cumulative inflow and cumulative demand. The first critical period is shown in Figure A-4, demonstrating a cumulative deficit of 669 KAF for a constant demand of 100 KAF/month, and a deficit of 2,600 KAF to supply a constant demand of 200 KAF/month. For 100 KAF/month, the period of deficit is from May 1976 through December 1977 (19 months), and for 200 KAF/month, the period of deficit is April 1976 to May 1978 (25 months). The second critical period, which extends for nearly seven years when considering demand of 200 KAF/month, is shown in Figure A-5, and produces a more critical result than the previous period for this larger demand. The slope of cumulative inflow is steeper (as seen when compared to the demand slope), because there are no years as dry as the first critical period. The cumulative deficit for a demand of 200 KAF/month is 4,068 KAF in this period, with deficit period from June 1986 through April 1995. The demand of only 100 KAF/month, when compared to the inflow slope, shows no significant storage need in this period, and so the result of the previous period is not updated.

(3) It is important to note that the two critical periods visible in this record are surrounded by normal years, rather than existing at the beginning or end of the record. If a critical period, visible as a flatter slope in Figure A-3, did appear at the beginning or end, the analysis would require the record to be wrapped (adding to the end years to the beginning or beginning years to the end) to create a complete critical period with normal years around it.

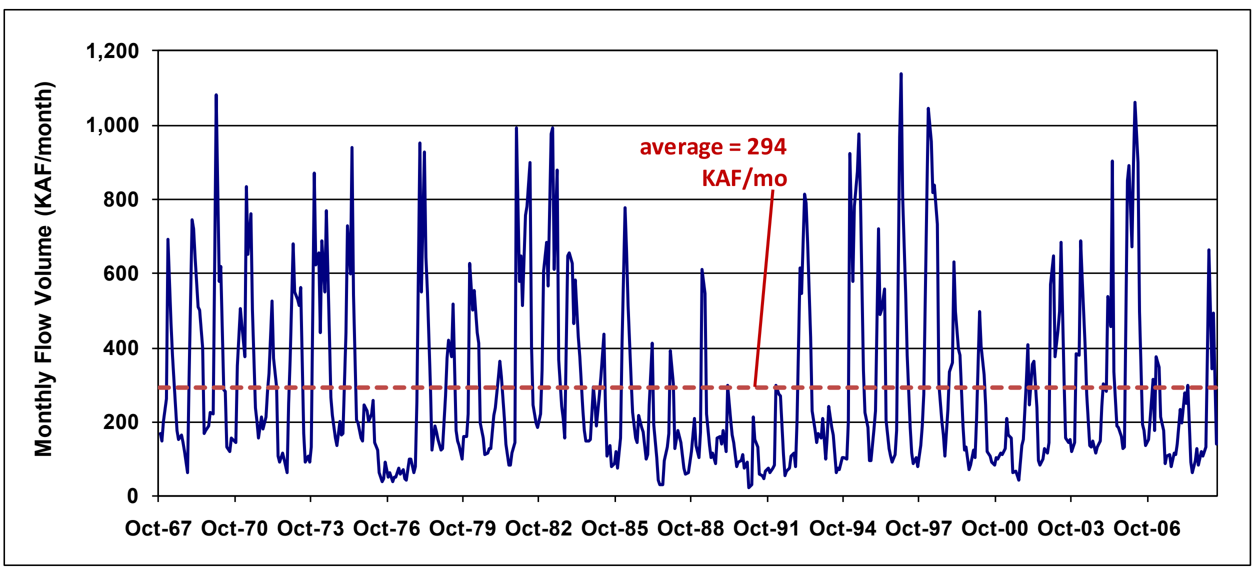

Figure A-2. Example inflow time series.

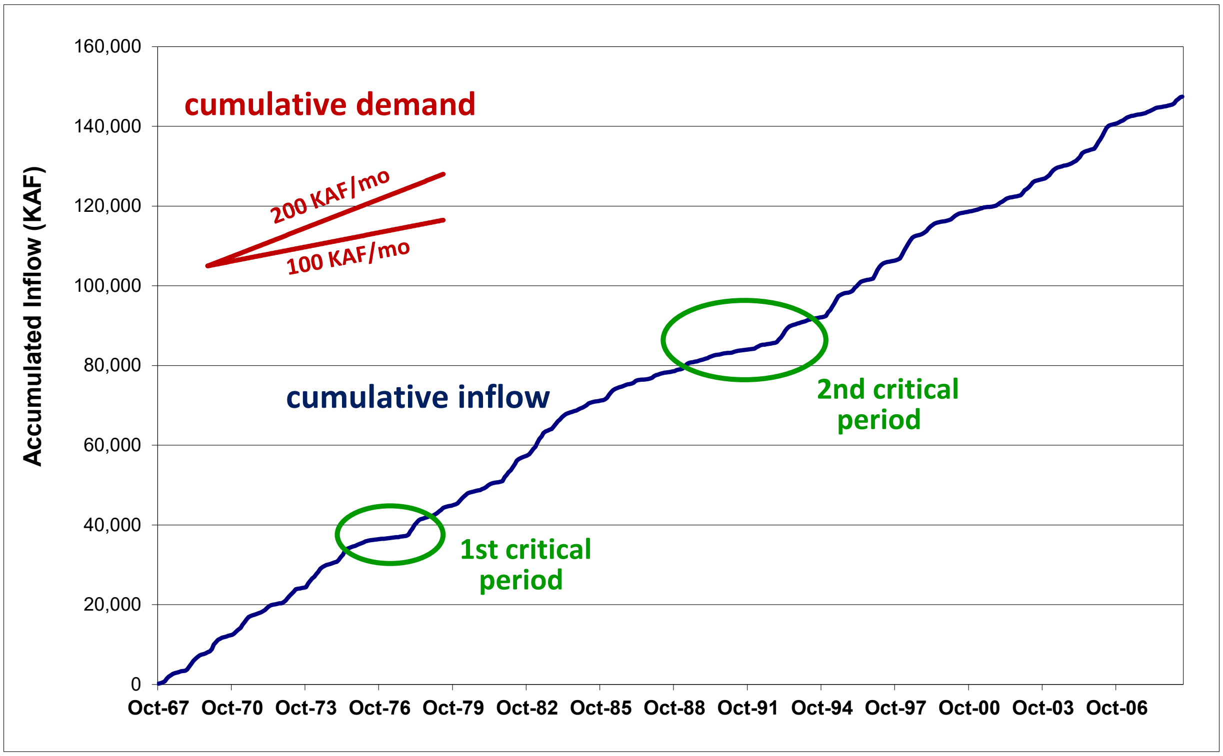

Figure A-3. Rippl mass diagram showing cumulative inflow and potential critical periods.

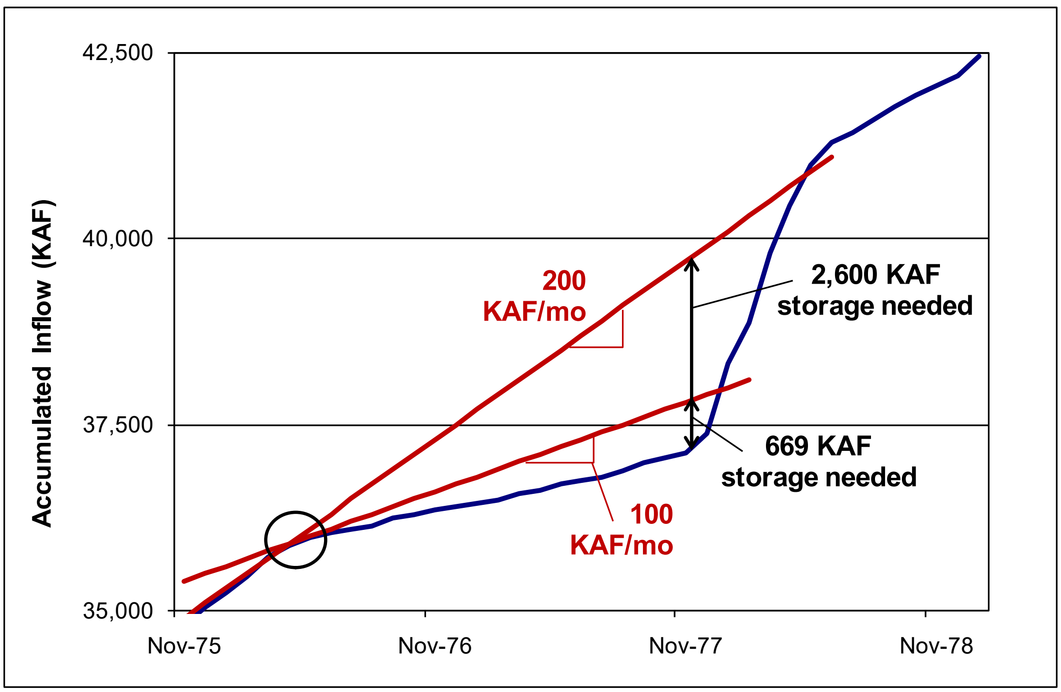

Figure A-4. Rippl mass diagram application of two demand rates for first critical period (mid-1970s).

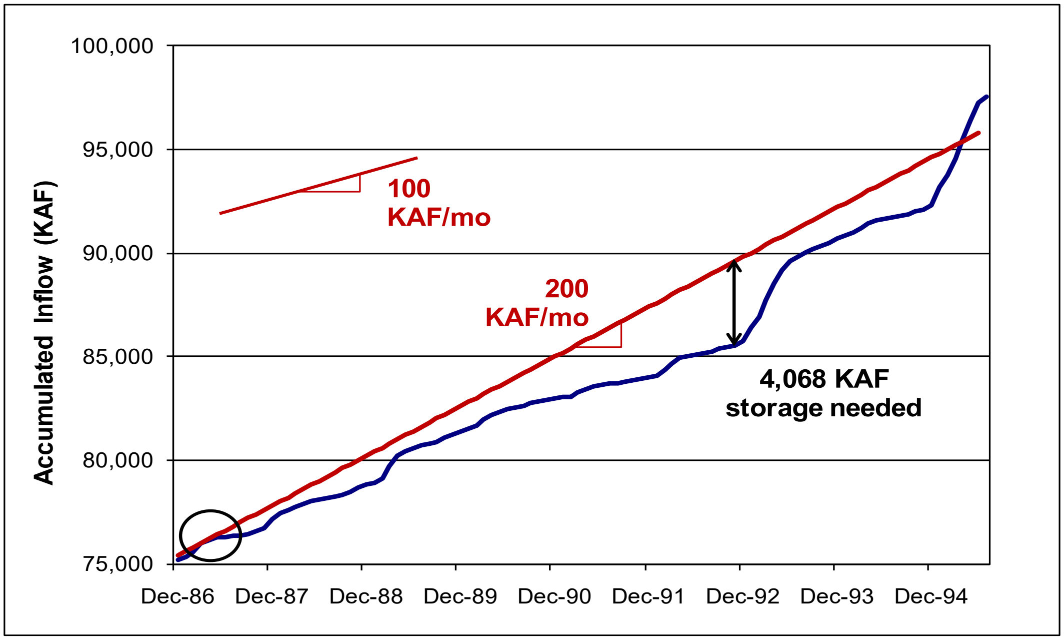

Figure A-5. Rippl mass diagram application of larger demand rate for second critical period (early-1990s).

(4) The slightly more computationally intensive Sequent Peak method allows a demand that varies seasonally, simply computing and accumulating the net inflow (inflow minus demand) in every time period, and plotting for the period of record. The plotted cumulative net inflow contains peaks and troughs, and the largest vertical difference between a peak and a subsequent trough defines a critical period and the stored water volume required to supply demand during that period. A variation on the Sequent Peak method that does not require a graphical component computes the deficit between inflow and demand (demand minus inflow) in every time period, and accumulates positive deficit over the period of record (see equation A-2).

$$Cumulative\ Deficit(t) = \max\left(0, \sum_{i=1}^{i=t} Demand(i) - Inflow(i)\right) \qquad \text{(A-2)}$$

(5) The largest accumulated deficit in the record is the amount of stored water required to meet the demand during the driest period, occurring during one of the critical periods. Repeating the accumulation of deficit for a larger demand rate will result in a larger maximum cumulative deficit, requiring a larger storage volume to meet that demand, and adding an additional point to the storage/yield relationship. The Sequent Peak method is shown in Figure A-6, plotting both accumulated net inflow in blue and accumulated positive deficit in pink for the entire record, with a demand of 100 KAF/month. The storage requirement is visible as both the maximum decrease in accumulated net inflow in blue, on the left axis, and the largest accumulated deficit in pink on the right axis. (Note: The right axis is reversed, to show deficit downward.) For the first critical period, storage requirement is again 669 KAF, for May 1976 through December 1977. Figure A-7 shows the method with a demand of 200 KAF/month. The storage requirement in the first critical period is again 2,600 KAF, and in the second critical

period it is again 4,068 KAF, for June 1986 through April 1995. (Note: The critical period is defined here as the time until the cumulative deficit has reached zero.) This method also demonstrates that for a larger storage volume and larger demand depicted in the 200 KAF/month case, it is the second less severe but longer dry period which defines the critical/firm yield.

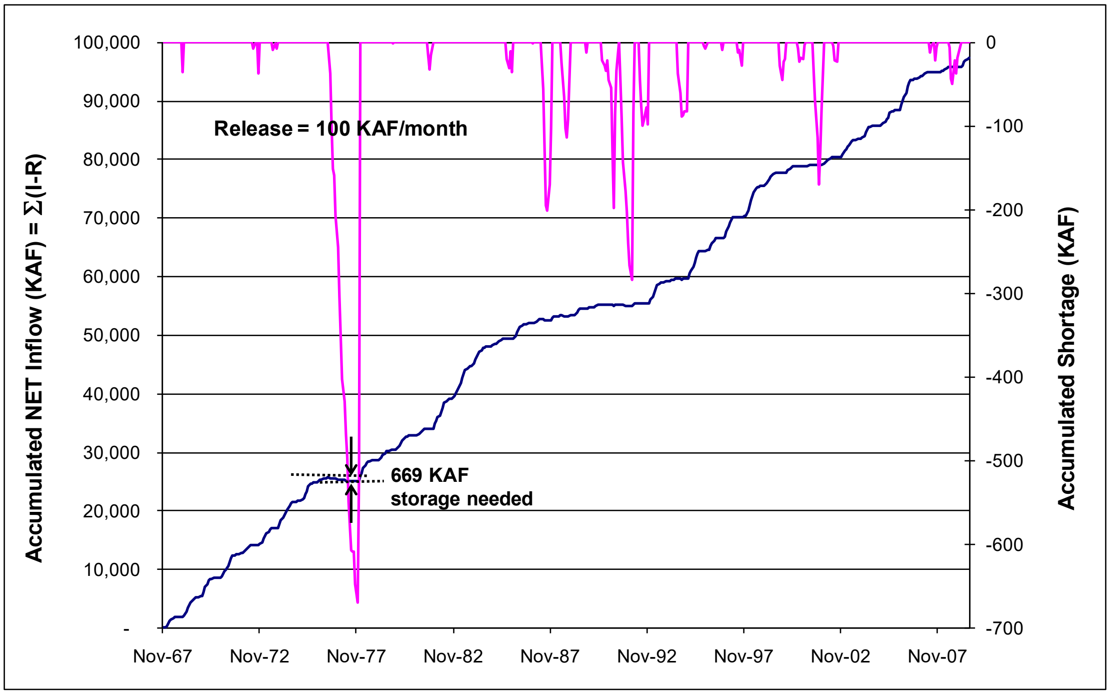

Figure A-6. Sequent peak algorithm for entire record with demand of 100 KAF/month.

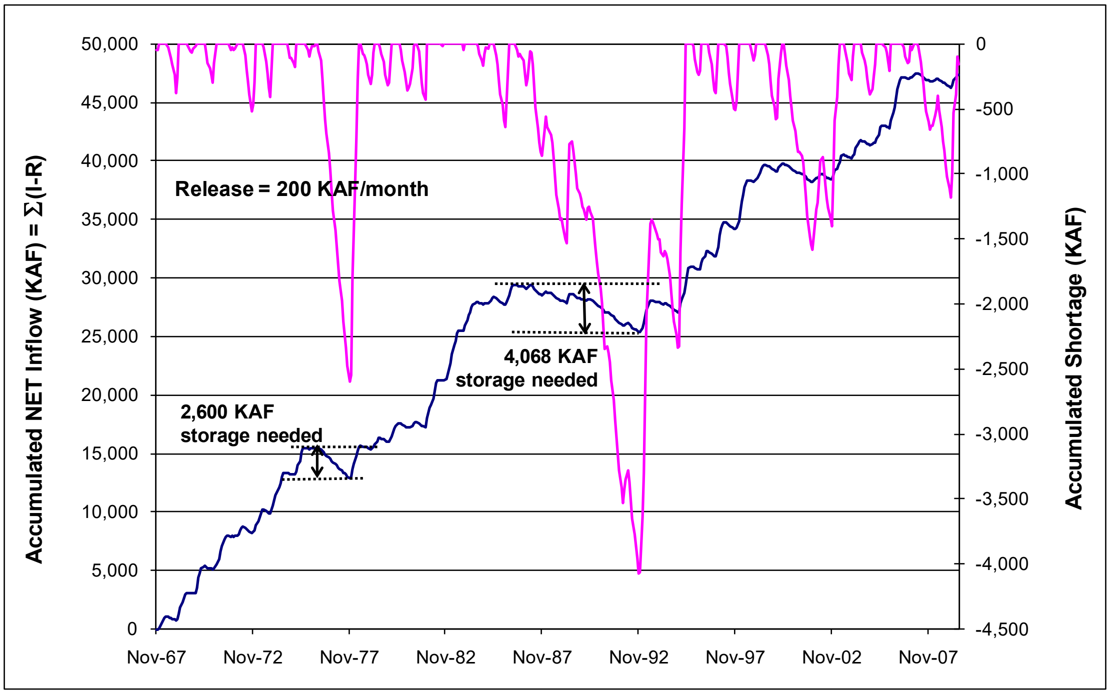

Figure A-7. Sequent peak algorithm for entire record with demand of 200 KAF/month.

(6) It was noted above that the two critical periods in this record are surrounded by normal years, rather than existing at the beginning or end of the record and so perhaps being incomplete. Figures A-6 and A-7 show a critical period by a dip in the blue line, or a downward spike in the pink line. If a critical period did appear at the beginning or end of the record, the analysis would require the record to be wrapped (adding years to the beginning or end) to create a complete critical period with normal years around it.

(7) The storage/yield relationship determined by these methods is shown in Figures A-8 and A-9, depicting the results of the first and the second critical periods (mid-1970s and early-1990s, respectively), showing when each is the driving relationship, i.e., provides the lower and so more critical firm yield, or higher storage requirement. The green curve is formed of a series of storage volumes needed to achieve a given yield rate during the first critical period in the mid-1970s. Similarly, the pink curve represents storage/yield pairings if one instead evaluated the second critical period in the early-1990s. The final storage/yield relationship is the lower of the two curves at each volume, shown in Figure A-8 as the dotted blue line and in Figure A-9 as the solid blue line. Often a storage/yield curve is extended to reach the storage required to develop yield equal to the average annual streamflow (or reservoir inflow), as displayed in Figure A-9 which includes the storage required to provide yield equal to average flow of 292 KAF/month.

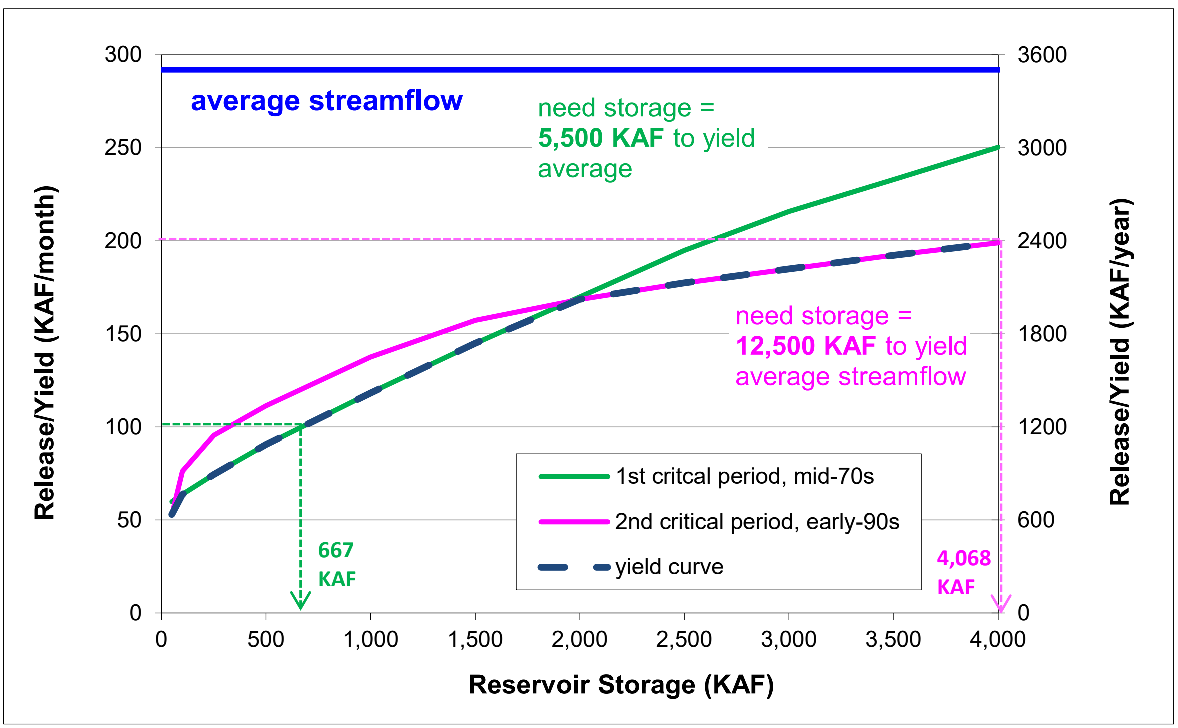

Figure A-8. Storage/yield relationships resulting from inflow series, two critical periods.

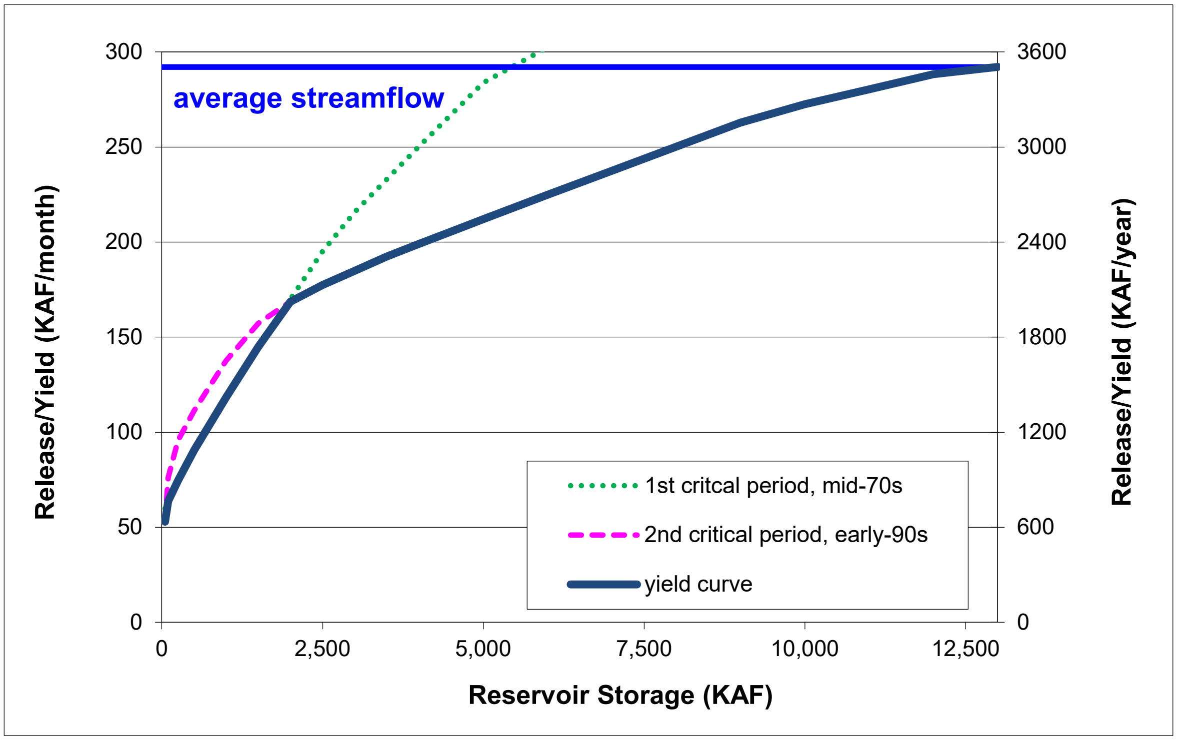

Figure A-9. Complete storage/yield relationship extended to average streamflow.

(8) A similar approach to storage/yield analysis uses linear programming optimization to represent simple reservoir mass balance across all time periods. Linear constraints capture continuity (change in storage between periods equals inflow minus outflow), reservoir capacity as an upper bound on reservoir storage, and demand as a lower bound on reservoir withdrawal. The objective function either maximizes a consistent withdrawal given a specified storage capacity or minimizes the storage capacity given a defined withdrawal rate. Computing such a model using period of record inflows would provide the same result as the simple methods that determine maximum deficit for a given demand.

(9) This demonstration of methods has been performed on a monthly time-step. A daily time-step is also possible for the Rippl Mass Diagram and Sequent Peak methods, and even for the optimization approach, although it would become computationally intense.

(10) Each of these simple methods focuses on computing a maximum cumulative deficit in supplying a specified demand and defines that amount as the required storage to supply that demand through the critical period. While this approach might be adequate for a preliminary analysis, it does not capture the impact of the reservoir pool (e.g., evaporation loss), realistic multi-objective reservoir operations, or interaction with other reservoirs and downstream supplies. Given the power of modern desktop computers, and the availability of sophisticated reservoir simulation tools, it is now more feasible than in the past to use an iterative reservoir simulation approach to determine the storage/yield relationship.

c. Iterative Simulation Approach.

(1) Using a simulation model of a reservoir or reservoir system that captures storage and release capacities and operation rules that meet system objectives, the goal in a firm yield analysis is still to determine the maximum flow rate that can be supplied without fail throughout the period of record. That maximum flow rate will exactly empty the reservoir pool once in the simulation period, during one of the critical dry periods. Iterative simulation is used to successively estimate the demand level to determine the level that exactly empties defined reservoir storage volume with no shortage. Figures A-10 and A-11 depict the simplest form of reservoir simulation that only computes mass balance, with inflow and release to demand (blue and pink lines) on the left axis, and storage level (yellow fill) on the right axis. The mass balance is shown in equation A-3.

Mass Balance: Storage(t) = max[Storage(t-1) + Inflow(t) - Release(t), storage capacity] (A-3)

(2) Figures A-10 and A-11 show that stored water is used (storage decreases) when inflow is less than demand and is restored (storage increases) when inflow is greater than demand. This simple simulation was performed with the same monthly data as used above for the Rippl Mass Diagram and Sequent Peak examples (though is plotted with storage in acre-feet rather than kilo-acre-feet), to show identical resulting required storage as paragraph A-4a. Figure A-10 shows a final demand of 100 KAF/month, having defined reservoir storage volume as 669 KAF, and Figure A-11 shows a final demand of 200 KAF/month, having defined storage as 4,068 KAF. Note: The reservoir storage exactly empties one time in each simulation, while satisfying the demand.

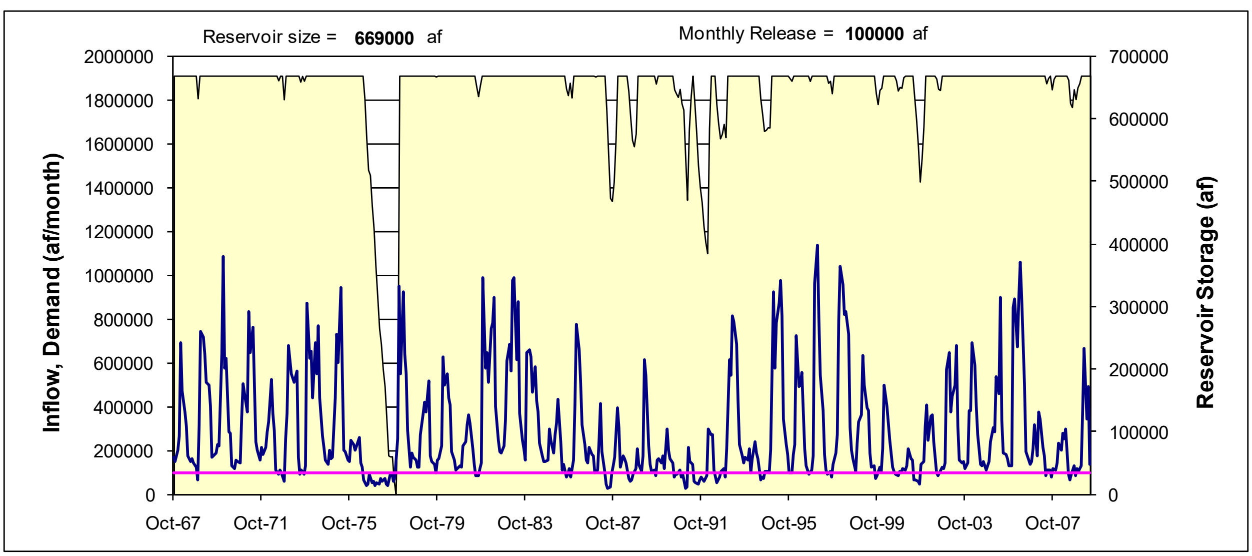

Figure A-10. Simple reservoir simulation with demand of 100 KAF/month.

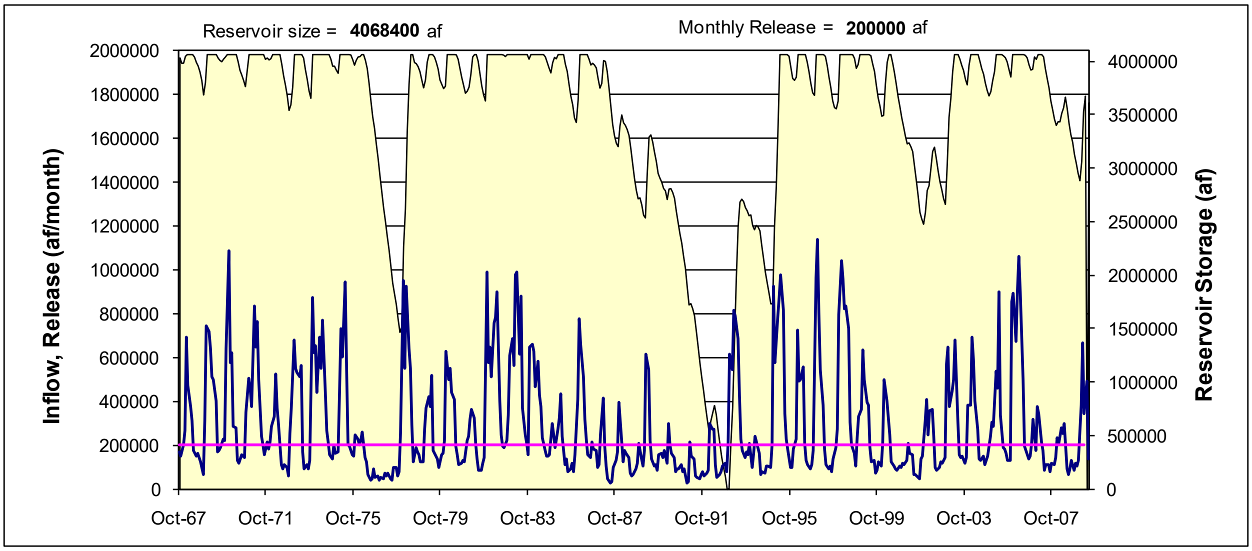

Figure A-11. Simple reservoir simulation with demand of 200 KAF/month.

(3) As noted above, it can be seen that the critical periods are within the record, rather than at the beginning or end, by when the reservoir level dips. If there were a critical period at the beginning or end of the record that was therefore incomplete, the record would need to be wrapped (adding years to the beginning or end) to create a complete critical period surrounded by normal years. Because the beginning of the record is not dry (reservoir storage does not dip), the starting level of the reservoir has little effect on this simulation. However, if there were any doubt about whether that beginning period is relevant, either it can be wrapped or the simulation can be started with the reservoir nearly empty to verify that it does fill. In this example, an additional simulation starting with the reservoir nearly empty shows it filling in the first year.

(4) Making use of the flexibility provided by the iterative simulation method compared to the simpler methods, the next examples demonstrate the effect of variable demand and variable storage volume on the yield provided by a given reservoir. Figure A-12 again displays a simulation of storage pool 4,068 KAF, but with a seasonally varying demand. Given that storage volume, the maximum possible average monthly release is somewhat lower than the 200 KAF/month for constant demand, at 198 KAF/month, but not dramatically lower. Generally, the misalignment of timing between natural streamflow and the need for water means that the assumption of a constant rather than varying demand can underestimate storage requirement, or equivalently, overestimate the firm yield. Figure A-13 adds to the above example a seasonally varying Conservation Pool that is reduced to create a Flood Pool during part of the year, shown as the dashed green line. The need to decrease the storage level by 1,000 KAF, and then attempt to refill when allowed, has a larger impact on the maximum attainable demand (the firm yield), lowering it by 9% to 182 KAF/month.

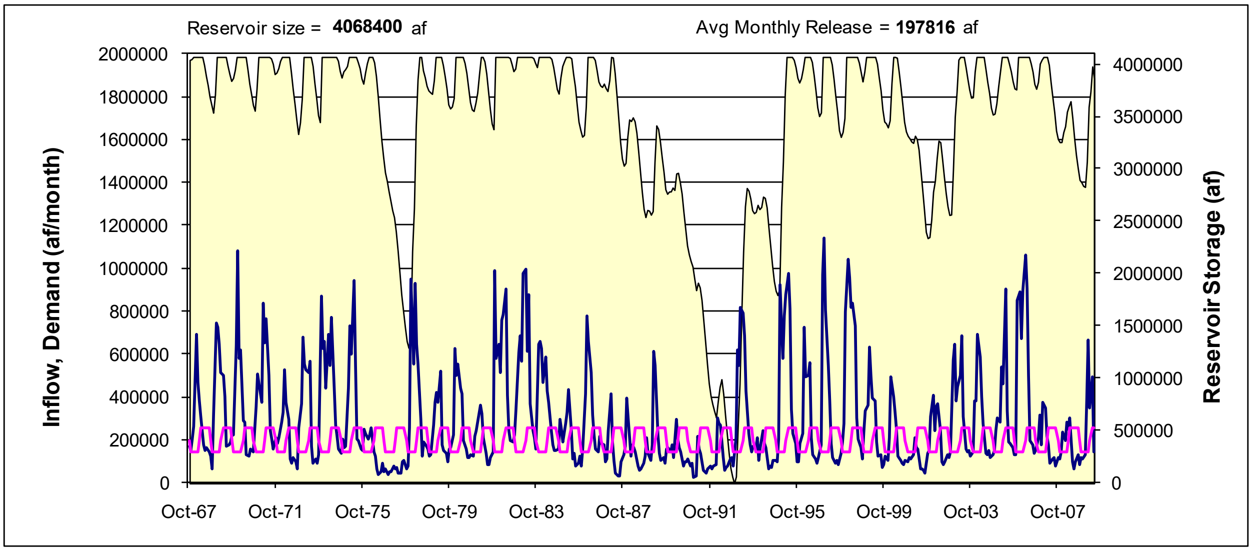

Figure A-12. Simple reservoir simulation with varying demand averaging 198 KAF/month (from 200 KAF/month constant demand).

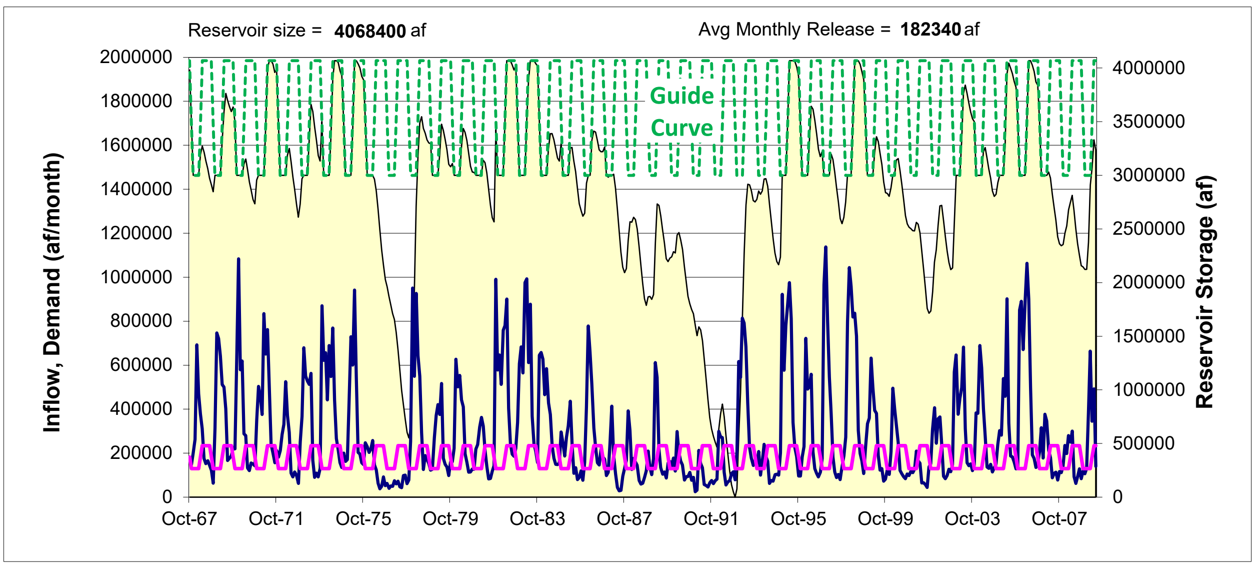

Figure A-13. Simple reservoir simulation with varying capacity up to 4,068 KAF, with demand averaging 182 KAF/month (from 200 KAF/month constant demand with constant storage capacity).

(5) This very simple, monthly mass-balance simulation was used to show iterative simulation results for constant demand and pool that are equal to the earlier simple methods (though different from variable demand and pool). The use of a more sophisticated reservoir simulation tool with the iterative simulation approach would likely provide different results. That difference would stem from the ability to capture reservoir losses, gains, returns, interaction with other reservoirs and downstream flows, and complex objectives. Another potential benefit of a simulation approach is the ability to specifically capture the operation for various project purposes and evaluate how those operations would change if adjusting allocation of reservoir

storage between purposes. Finally, when computing the firm yield for uses other than an at-site withdrawal requirement, the need to simulate the reservoir system as a whole is essential.

(6) The Conservation Pool of a federal reservoir can support many uses and objectives and provide some yield for each of those uses. Because water supply firm yield can be stated in terms of a demand for water at some rate, the simpler methods can provide an estimate of a storage requirement to meet that demand, and perhaps an entire storage/yield relationship. However, some other types of yield cannot be specified simply as a flow requirement. Hydropower demand is stated as an energy requirement, and the required release rate to meet that requirement varies depending on the reservoir elevation (head on the turbine). To assess hydropower yield, the reservoir storage (head) and hydro-turbines must be simulated with some level of detail. Other examples of more complex water needs/demands are the flow rate required for downstream flow augmentation, which depends on the local inflow to the stream below the reservoir, and for water quality requirements, which depends not just on the magnitude of downstream flows but their quality. For these types of yield, which are additional uses of the reservoir Conservation Pool, reservoir simulation is essential to compute storage requirements for various levels of demand, as the simple methods would not be adequate. For water quality, a reservoir simulation tool is needed that has the ability to evaluate and track water quality (i.e., temperature, dissolved solids, BOD/biochemical oxygen demand) and define operations to meet quality standards.[1]

(7) Optimization techniques have also become more tractable with modern compute power. The linear programming (LP) optimization approach described above can maximize the minimum release across the period of record, respecting storage balance and inflow in the continuity equations. This approach offers a similar result to iterating a simulation to find the largest consistent release that can be achieved but does not require iteration. However, using an optimization model usually requires simplification of the reservoir system and its operations, and so it is difficult to get the same resolution of the water system operations in an optimization as with a simulation. The iterative simulation approach, although perhaps less efficient, can allow a far more detailed system operation that more explicitly captures existing or proposed operating rules. Faster compute times have made the iterative simulation approach more reasonable than in the past, and it is the focus of this document.

A-5. **Required Inputs (Historical Data Record).**

a. Available Inflows, Evaporation, Precipitation, Historical Withdrawal/Return.

(1) The element of the water system having the greatest impact on the storage/yield relationship is the streamflow time-series. The streamflow time-series defines available water and the rate at which the water arrives, which is the essential element to supplying a water

1 As of the writing of this document, the USACE reservoir simulation software HEC-ResSim currently does not easily evaluate water quality. However, HEC-5Q (USACE, 1986) and CE-QUAL-W2 (Cole, 1995) are plug-ins to HEC-ResSim to allow this interactive estimate of water quality yield or storage requirement.

demand of any kind. Demand that is less than available streamflow at all times requires no storage, and demand that is sometimes greater than available streamflow necessitates the ability to store water to supply the demand in those times of deficit. The storage requirement for a demand is dependent on the water available throughout a critical dry period, but the bounds of that critical period may vary with the magnitude of that use, occasionally being a different period all together.

(2) Documents from HEC (USACE, 1967; USACE, 1975) include good discussions on preparation of the inflow series, as well as what types of losses should be considered and how to develop that data. This document covers those topics in less detail. When the available streamflows are the computed inflows to a reservoir, they have been computed as the change in storage plus measured outflow, as shown in equation A-4.

$$\text{Inflow}(t) = \text{Storage}(t) - \text{Storage}\ (t\text{-}1) + \text{Outflow}(t) \qquad \text{(A-4)}$$

(3) The computed inflow is therefore a net inflow, with evaporation and leakage already absent, and precipitation on the pool already present. Withdrawals from the reservoir pool and returns to the pool are also already captured within the computed inflow. To evaluate the storage need of a reservoir or Conservation Pool that might operate differently than it currently does, or is some other size than the existing pool, it is important to correct the inflows to be as close as possible to natural streamflows with no reservoir present. Therefore, inflow must be adjusted to remove the effects of evaporation, precipitation, leakage, past withdrawals from the reservoir, and past returns. The reservoir simulation must then recapture the evaporation, leakage and precipitation on the pool resulting from the reservoir levels simulated, as well as recapturing withdrawal and return in the determination of firm yield. Accurate precipitation and evaporation are extremely important because the storage requirements will be determined by a drought period in which evaporation is likely quite high and precipitation low. The practice of using average monthly evaporation rates is a reasonable beginning to determine the likely critical periods, but a record of measured evaporation from somewhere nearby, that demonstrates higher rates during the critically dry periods, will be much more valuable.

(4) When evaluating the storage requirement of an existing objective within the current Conservation Pool, there will perhaps be less change in the resulting reservoir levels than there would be in an evaluation of maximum yield (requiring more storage), and so the adjustment of the inflow series to remove these effects is therefore less important. However, it remains good practice to make these adjustments and capture these effects in simulation.

(5) Thus, the data required for a firm yield analysis is a period of record inflow, evaporation, and precipitation, as well as withdrawal and return data for periods they existed. The adjustment of the inflow time series must account for any factor, such as evaporation, that would differ from the historical result in a simulation of the proposed operation in a critical period, and the simulation must then account for that factor accurately.

b. Water Rights.

(1) In the Western United States, reservoirs generally operate within the Prior Appropriation water rights system. The portion of the inflow belonging to a reservoir, and therefore available to develop yield, is determined by the individual water rights. For the historical period of record, these amounts (flow rates and volumes) can be determined and used in the yield analysis. Where operation of the reservoir would affect the downstream users to the point of affecting the call on the river (i.e., the most junior water right that can be satisfied), the amounts may need to be re-determined within the reservoir analysis, which is a much more difficult task.

(2) In the Eastern United States, reservoirs generally operate within the Riparian water law system. Supply and shortages are proportionally shared by users on the river, upstream and downstream. For a given reservoir, the operation of an upstream reservoir affects the available inflow, and the needs of a downstream reservoir might be seen as a release requirement. The interaction between reservoirs is therefore important to capture, and in this document will be discussed in paragraph A-11.

(3) It is important to note that water rights of either type are the purview of the States, and not the Federal Government. USACE reservoirs are operated pursuant to federal law and authorities. USACE does not have a national policy on how to manage water rights nor allocate shares of inflow.

A-6. **Computation Time Interval**.

a. The simple methods demonstrated above can be performed on data of various time intervals and were demonstrated here with a monthly time-step. More sophisticated reservoir simulation tools can compute at a daily time step. If data is available at a daily time interval, and the compute tool is efficient, results at a daily time step can be more accurate. But given the option of using simple methods, which can be more easily performed on longer time steps, it is interesting to note the difference in the computed storage requirement for a given firm yield at various time steps.

b. A streamflow time series for a site in Pennsylvania, with its average annual flow of 2,030 cfs, is shown in Figure A-14. Figure A-15 displays the storage/yield curve that results from evaluating this flow time-series at a daily time interval. (These flows and the resulting relationship are used only as an example of firm yield computation and are not the results of a USACE study.) The storage/yield curve is colored and labeled to designate the critical period that defines each storage/yield pair. Note that smaller storage providing smaller firm yield has its critical period in either 1991 or 1999, which are the driest years during the Summer/Fall low-flow season. Moving up the storage/yield curve, as the storage becomes large enough to withstand those single-season dry periods that are quickly recovered by higher winter/spring flows, the critical period becomes the early 1950s and then the mid- to late 1960s, neither of which has individual seasons as dry as 1991 or 1999, but having longer periods of below-average volumes with less flow during the wet seasons.

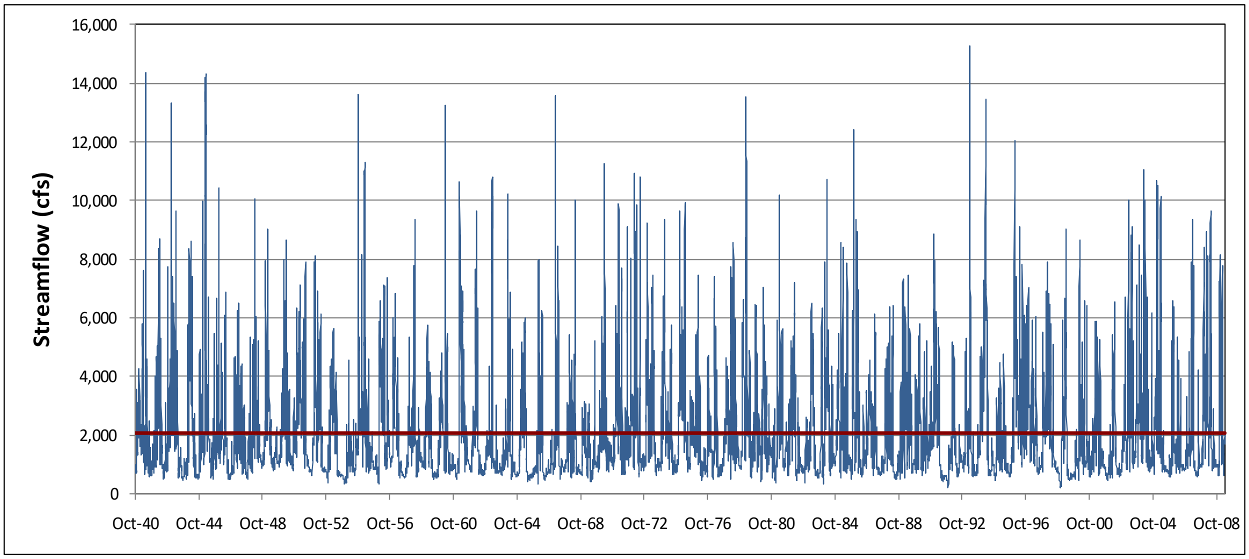

Figure A-14. Streamflow series, with average annual flow of 2,032 cfs.

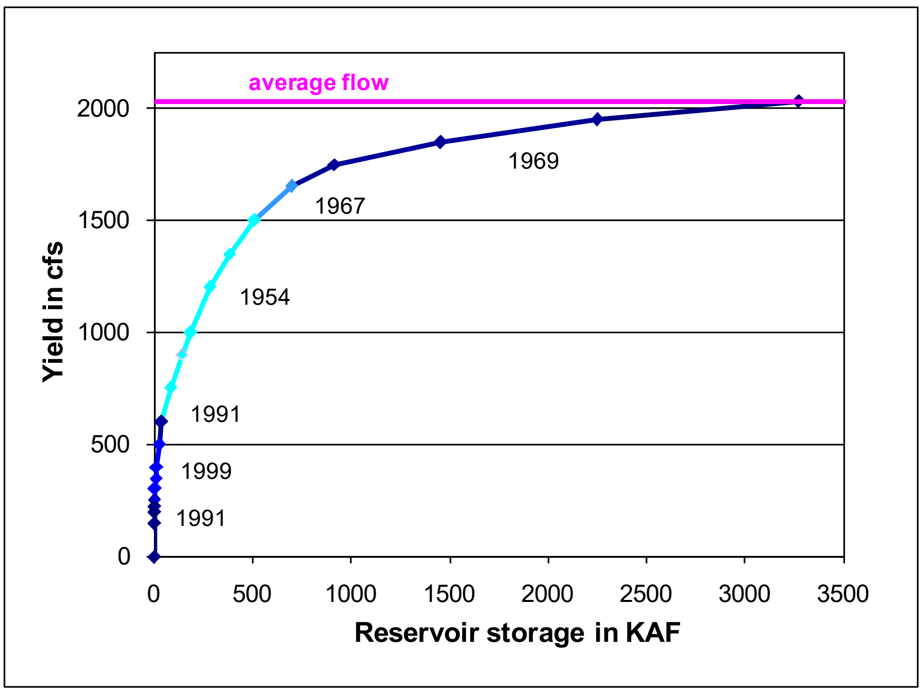

Figure A-15. Storage/yield relationship for streamflow time-series in Figure A-14.

c. Figure A-16 displays the data from Figure A-14 at increasing time intervals, consolidating to half-month, one-month, three-month, six-month and one-year. The variability in the flow is clearly reduced (smoothed out) as the time-step increases. Storing water also has the effect of smoothing the variability in flow and is the primary reason we build reservoirs. An important question is how much smoothing can be allowed to take place in advance of the analysis (by averaging the flows over a longer time-interval), and how much inflow variability must be retained in the simulation to determine an accurate storage requirement. The results of performing the storage/yield analysis on this data, at the various time-intervals, are shown in

Figure A-17. The curve from the daily analysis displayed in Figure A-17 is included as a solid blue line, along with the curves produced from longer intervals. In each case, if different from the shorter interval, the longer interval gives a less critical result appearing to the left (and above), meaning a smaller storage requirement to produce a given firm yield, or identically, a larger firm yield from a given storage capacity. This outcome is expected, because the decreased variability in the longer interval data decreases the storage need. In this example stream location, which has a wet and dry season within each year that causes most of the need for storage, the annual interval that combines these seasons is not expected to be adequate.

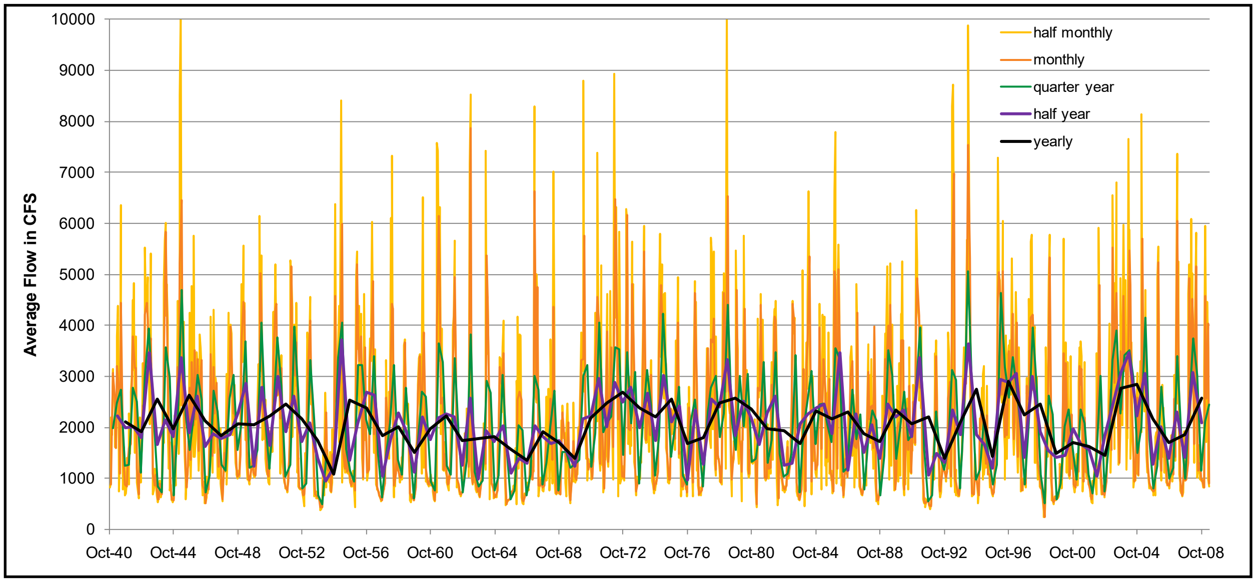

Figure A-16. Streamflow time-series in Figure A-14 with increasing time intervals.

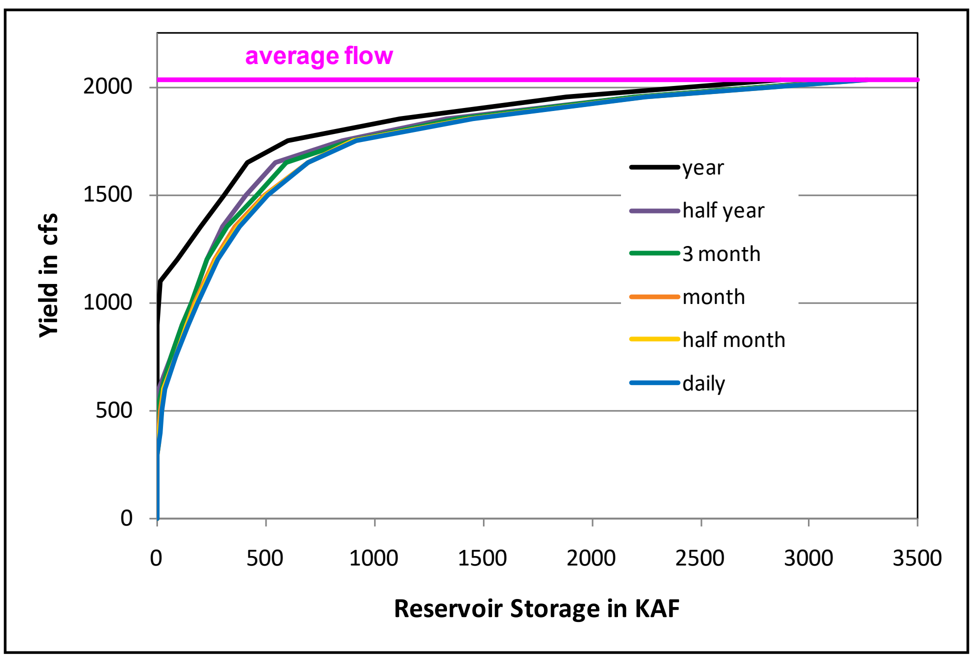

Figure A-17. Storage/yield relationship formed with data at increasing time intervals.

d. Figures A-18 and A-19 display the series of storage requirement simulations for a firm yield of 1,500 cfs at the different time intervals, showing only the years around the critical period of 1953 through 1954. (Note: In these simulations, the computation is reversed, and ***demand is specified*** at 1,500 cfs, with successive estimates of storage capacity used to determine the storage requirement.) In these figures, storage is shown as yellow fill (on the left axis), and inflow and release to demand as lines (on the right axis). In these simple simulations, it can be seen that storage is used when the inflow (blue line) is less than the demand (red line). There must be enough stored water to last through the critical dry period while meeting the demand (estimated firm yield), and that minimum amount of storage defines the storage requirement.

e. Figure A-18 shows the storage requirement simulations for daily, half-month and monthly intervals. The daily time-interval storage requirement of 511 KAF is assumed to be the most accurate estimate. The half-month and monthly time intervals call for slightly less storage at 503 KAF and 496 KAF, respectively. In figure panes for intervals longer than daily, the green dotted line shows the storage requirement computed for that time-interval, and the solid black line is the 511 KAF storage requirement from the daily compute. While there is loss of detail and smoothing of the flow extremes with the longer intervals, this effect impacted the result by only 3%.

f. Figure A-19 displays similar simulations at three-month, six-month, and yearly time intervals. These results show a larger difference in storage requirement, with three-month and six-month providing storage requirements of 461 KAF and 412 KAF, differing from daily by 10% and 20%, respectively. The averaging of flow across a longer time window has the effect of blending the periods of high and low flows which are the reason for needing stored water to satisfy demand. However, the three-month and six-month intervals are at least able to separate the wet time of year from the dry, capturing the within-year need to store water during the wet season to meet demand during the dry season. The yearly interval in the final pane suggests a storage requirement of 308 KAF (40% difference), which captures only the over-year storage required in a dry year and does not see the within-year storage requirements of nearly every year at this demand level.

g. Although a demand of 1,500 cfs was chosen for this example to show the differences between results at increasing time-intervals, it can be seen from Figure A-17 that at many demand levels (on the horizontal axis), the difference between the storage requirements for the various intervals (other than annual) is quite small. In fact, with the exception of demand levels between 1,200 and 1,600 cfs, the monthly computation produced a storage requirement within 1% of the daily computation. This result implies that for a computation of constant demand (firm yield), a monthly or even three-monthly time-interval could be adequate. However, analysis of streamflow augmentation and hydropower operations requires reservoir simulation at a shorter time interval. The remainder of simulations in this document use a daily time-step.

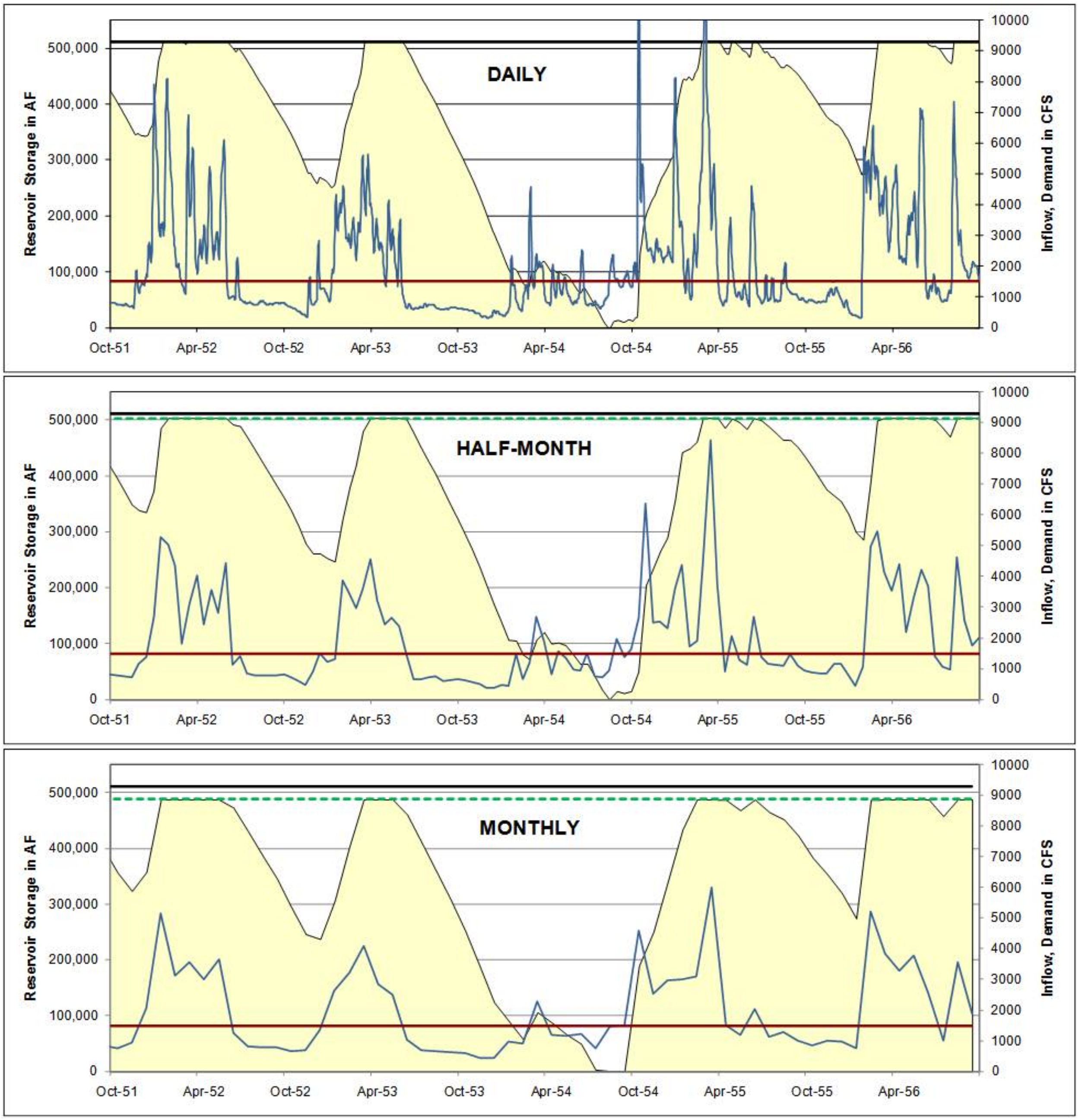

Figure A-18. Reservoir simulation to determine storage requirement for firm yield equal to 1,500 cfs for increasing time intervals (daily, half-month, monthly).

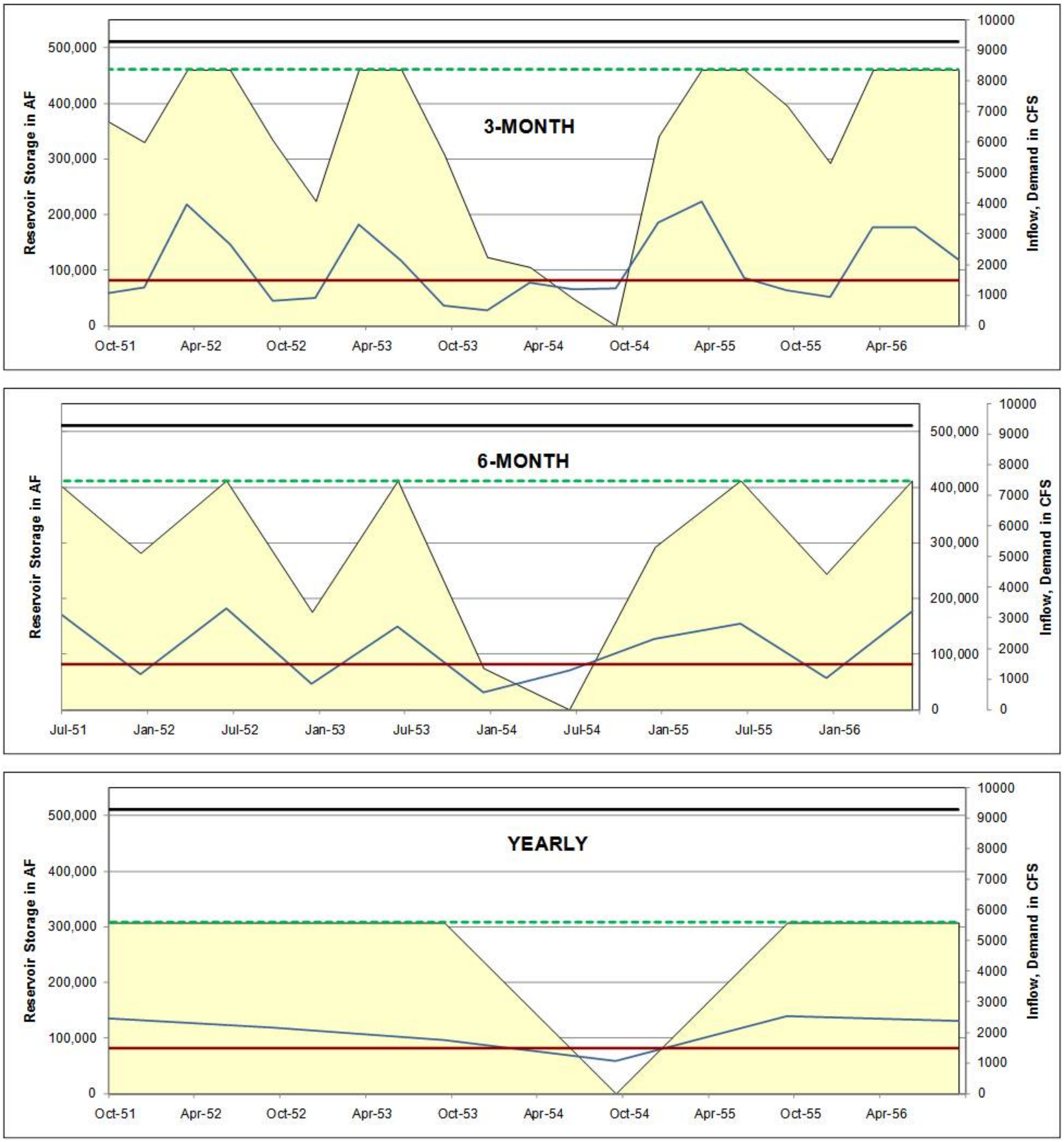

Figure A-19. Reservoir simulation to determine storage requirement for firm yield equal to 1,500 cfs for increasing time intervals (three-month, six-month, yearly).

A-7. **Impact of Reservoir-Based Losses and Gains on Yield**.

a. The storage/yield relationship shown in Figure A-15 was initially developed using one of the simple yield methods (the Sequent Peak algorithm), with an identical result then demonstrated using iteration of a very basic simulation. However, one of the benefits of using an iterative simulation approach is the ability for a more detailed model to capture losses and gains based on the reservoir pool, such as evaporation, leakage or rain directly on the pool. Evaporation, for example, is a function of the reservoir pool's surface area, and can amount to a substantial volume of water during hot and dry times of year.

b. Evaporation.

(1) An evaporation time-series that represents measured evaporation depth near the site of interest would be most useful in simulation, but often monthly average values are defined and used for all years. Such repeating monthly averages are least satisfactory during the critical period, which is most likely extremely dry, because evaporation during that period would likely have been higher than the average values, and so effort to find measured evaporation during the critical period is valuable. Figure A-20 shows how the storage/yield relationship originally shown in Figure A-15 is altered with daily evaporation (evaporation depth times reservoir surface area) subtracted from the reservoir storage within the simulation, shown as the red dotted curve below the initial curve.

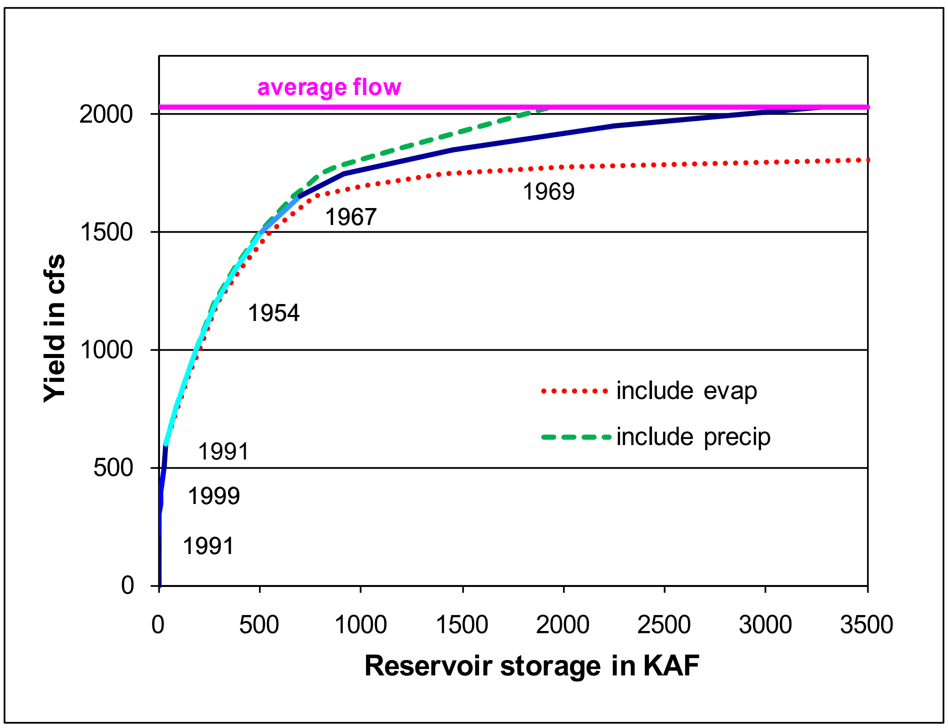

Figure A-20. Impact of evaporation and of precipitation on storage/yield relationship.

(2) Note: There is no difference in storage requirement for small firm yield, when the critical period is a single season. This result occurs because the 1991 and 1999 critical periods are in winter, and the suggested evaporation for this area of Pennsylvania is zero in the winter months. Simulation of higher yield that has critical period 1953 through 1954 shows an increase in the storage requirement for firm yield greater than 700 cfs when evaporation is considered. As seen in Figure A-20, significant differences occur above a firm yield of 1,500 cfs. For this example, the shape of the reservoir (surface area versus volume) was fabricated as an extension of the relationship for a reservoir at another site. The relationship might be less reasonable for the extremely large storage volumes needed to develop the average flow of 2,030 cfs as firm yield.

c. Rainfall on the Pool.

(1) Water volume gained from rainfall directly on the reservoir pool is also a function of its surface area. All rain falling on the pool "flows into" the reservoir, whereas without the reservoir present some of it would have infiltrated the ground and not reached the stream, and so not have been included in the natural inflow. To capture rain-on-pool, an estimate of the percentage of the rainfall that is "gained" by the reservoir versus the percentage that would have reached the stream anyway (and is therefore present in the inflow estimate) must be determined. Most accurately, this percentage of gain would be determined per rainfall event. Most simply, a single percentage could be specified for the entire simulation. A time-series of precipitation from a nearby gage is used to define the depth of rainfall on the pool and the additional inflow volume is computed by multiplying that depth by surface area, and multiplying by the percentage of "gain." The assumption of rain falling equally on the pool is weaker than the assumption of equal evaporation from the pool, but it is a reasonable assumption, nonetheless. Figure A-20 also shows how a storage/yield relationship is altered when rain-on-pool is computed with a 50% gain (shown as the dashed green curve above the original curve). Figure A-21 shows the resulting storage/yield curve with both evaporation and rain-on-pool considered, and adds that result as the long-dashed gray curve. Note that the combined effect of evaporation and precipitation is lower than the initial curve, implying that evaporation at this site is greater than precipitation during the critical periods, producing a net loss.

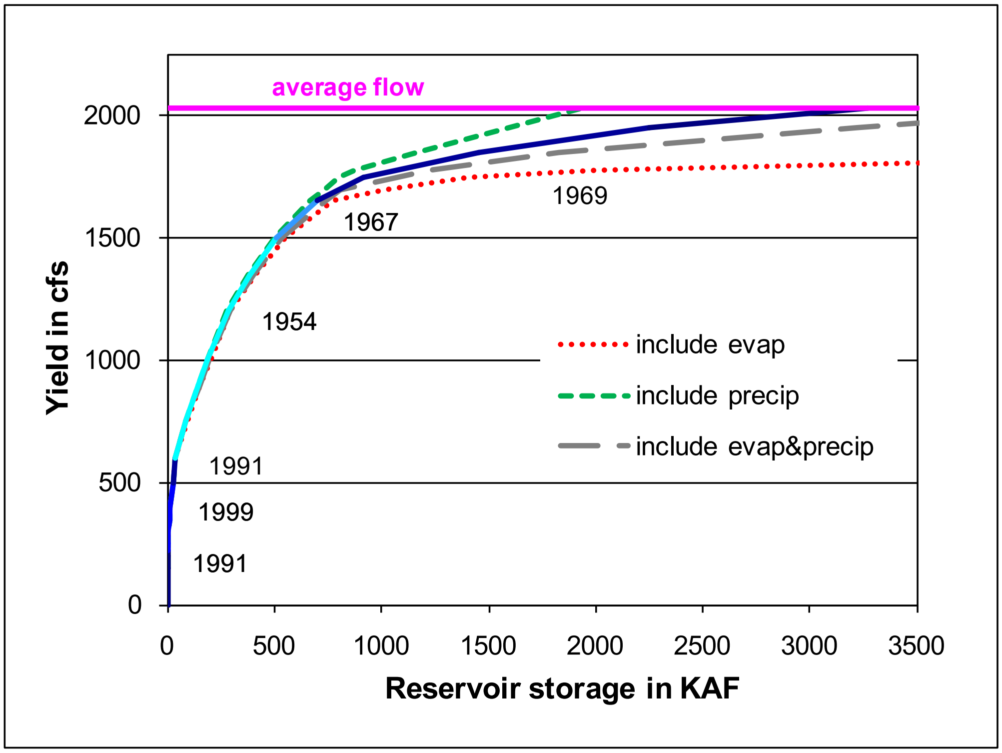

Figure A-21. Impact of both evaporation and precipitation on storage/yield relationship.

A-8. **Operation of a Reservoir Providing Firm Yield**.

a. Traditionally, the operation of a reservoir to serve multiple objectives (flood protection, recreation, water supply, navigation, flow augmentation for water quality or habitat, hydropower) is studied before the reservoir is built, and a set of operating rules anchored by a Guide Curve is defined to govern the interaction between those purposes. The required Flood Pool volume is the space above the Guide Curve and is kept empty except when detaining flood water. The Conservation Pool is defined as the volume below the Guide Curve (but above Inactive storage) and is kept as full as possible while meeting water needs. Some reservoir uses such as pool recreation prefer a constant reservoir level, and development of recreational facilities would consider a range between the Guide Curve and some increment below it as an expected operating range. Uses that require releases from storage to the channel or to locations away from the reservoir (e.g., M&I water supply, irrigation, navigation or minimum flows requirements) instead use the reservoir as temporary storage to allow inflows arriving at an inopportune time to be held and used when needed. These uses are not concerned with the reservoir level, but merely its contents, and satisfying them “consumes” the water from the reservoir. Hydropower is a use that depends upon both level and contents because hydropower operation requires adequate head (reservoir storage level) and also releases water from storage. Traditionally, adequate head is maintained for hydropower by defining an inactive reservoir pool below which water cannot be drawn, maintaining head as well as providing volume for sediment entrapment. Water stored above the Inactive pool can then be released to drive the turbines (as well as satisfy other purposes). It is assumed that the Inactive Pool level represents a head level below which the hydro-turbines cannot be operated.

b. There is the potential for using inactive storage volume that was originally intended for providing hydropower head to meet demand during drought as an emergency supply. This practice is similar to reserving the inactive pool for both hydropower head and for meeting needs that require a higher priority. If the firm yield for water supply were planned without the inactive pool, its use will provide a factor of safety against occurrence of a drought more severe than the historical worst drought, or critical drought. In some cases, reserved storage for a use that requires higher reliability could be predefined, as described in paragraph A-10 in the discussion of supply reliability.

c. Complementary Uses.

(1) For reservoir uses defined by a firm or critical yield, as described within this document, the greatest challenge to supplying those uses comes during critically dry periods (which is the reason those periods are used to define yield). In wet years, needs might be met by inflow alone, and in the greater portion of years, needs might be met by inflow plus a small amount drawn from storage. Therefore, in a reservoir that devotes a great deal of its volume to "consumptive" uses, much of the time the reservoir might remain high, near its Guide Curve. Only in critically dry times would the pool be drawn down to a low level. Uses such as hydropower that can take advantage of high head from a mostly full reservoir much of the time, and meet their demand by some other source during critically dry times (for example, using thermal plants), are a good complementary use with water supply. Flood protection is a good complementary use with water supply for an area that experiences higher flood risk (needing an empty flood pool) during some times of the year but not others, as discussed below in paragraph A-8b, Seasonal Guide Curve.

d. Seasonal Guide Curve.

(1) Many Federal reservoirs designate some portion of the storage volume to flood protection, keeping that volume empty in preparation for flood detention, and some portion of the volume to conservation storage, keeping that volume as full as possible while meeting "consumptive" needs. The Guide Curve is the line dividing the reservoir between the Flood Pool and Conservation Pool. In many areas that experience flooding, the flood risk is seasonal, and there are times of the year when there is no danger of flooding. In these areas, a seasonal pool can be defined which is designated as flood space during the flooding season and conservation space the rest of the time.

(2) In regions that experience flooding mainly from rainfall events, the water detained during a flood event is then evacuated from the flood pool to prepare for another event. But when the flood season ends, the seasonal pool is allowed to fill, becoming part of the Conservation Pool. The Guide Curve is therefore a seasonal line, as depicted above in Figure A-13. Areas such as the Western Sierra experience snowmelt runoff after the rain-flood season ends, allowing the seasonal Conservation Pool to fill with snowmelt runoff after danger of rain-floods has passed. However, this beneficial timing does not exist in all rain-flood regions, and in many cases the ability to refill the reestablished conservation volume each year is in question.

(3) In regions that experience flooding mainly from snowmelt runoff, the intention is for the flood runoff itself to fill the seasonal pool, ending the snowmelt flood season with the reservoir full. Because there is some ability to forecast the snowmelt runoff by observing the volume of water "stored" as snow upstream of the reservoir, the Flood Pool can be carefully sized each year, being only as large as needed (with some hedging against uncertainty in the forecasted volume), allowing a more successful transition between the empty Flood Pool and a full Conservation Pool.

(4) A seasonal Guide Curve by definition allows a different amount of conservation storage at different times of the year, and so the relationship between storage and firm yield can no longer be described by a single curve that pairs available storage volume with the firm yield it can provide. If a 100 KAF constant pool level provides 1,000 cfs, and a 200 KAF constant pool level provides 1,500 cfs, the firm yield resulting from a seasonal pool that changes between 100 KAF in the flood season and 200 KAF in the conservation season would provide firm yield somewhere between 1,000 cfs and 1,500 cfs (or, depending on timing of draft, perhaps equal to one or the other). Iterative simulation of the reservoir operation following the seasonal Guide Curve and maximizing the release would determine the resulting firm yield. However, the relationship between storage and firm yield would no longer be a simple, single storage/yield curve, because there are multiple storage levels that provide a given yield.

e. Horizontal Reservoir Pools versus Floating or Vertical Pools (Storage Accounts).

(1) USACE, 1975, has a suggestion about the division of storage space within a reservoir. "*Unless allocation of space to specific purposes is directed, specific allocations of space should be* avoided in favor of operation rules based on total remaining storage." Defining rules based on total remaining storage is a method which divides the reservoir into horizontal zones, with the operation rules changing as the reservoir level moves from zone to zone, constraining or removing some lower priority uses as the reservoir storage gets lower, and invoking flood operations when the reservoir is high. Presumably, this suggestion to operate solely by zones was made to reduce complexity in the operation of a reservoir, and eliminate the need to carefully account for the use of water by different purposes. However, with the needs for reservoirs changing, and operational purposes being added, careful assignment of reservoir volume and accounting for the use of that volume may become necessary. Further, there is now a greater ability to perform detailed accounting of water use than when this suggestion was made.

(2) As described above, the traditional way of dividing a reservoir's volume is into horizontal pools is an approach that works very well for the division between flood volume and conservation volume, and also for the retention of hydropower head with an Inactive Pool. This division is also effective for reservoir recreation, which benefits from a target reservoir level defined by the Guide Curve, the line between the horizontal Flood and Conservation Pools.

(3) For conservation uses, multiple horizontal pools are a way of changing the intensity of use based on the state of the Conservation Pool as a whole. When lower zones are reached, use can be decreased (impacting reliability) to allow lesser use for a longer period. This approach delivers water at a normal rate until supply (stored volume) is low, and then delivers at

a decreased rate thereafter, until the next zone is reached. For a single conservation use, a drought operation plan might be defined to determine the zone levels (volumes) at which to reduce use, and the amount to reduce. For multiple conservation uses, when one use is clearly a higher priority, other uses might be reduced when a lower zone is reached to allow the high priority use to continue for longer than it would have with full use by all. An unfortunate effect of this operation is that it is possible for one use to drain the pool to a level that other uses are then restricted, even if they had used no water while the pool was drained. This effect is a problem that can be solved with specific allocations of water user accounts.

(4) An alternative to dividing the various conservation uses with horizontal pools (zones) is to assign storage accounts to individual users of the Conservation Pool. User storage accounts can be thought of as vertical or floating segments of the Conservation Pool. A user is assigned some volume of space, and so has some maximum volume of water it may store in its account. A share of the reservoir inflow is credited to its account and its use is withdrawn from its account. Water or storage accounting tracks the balance of the account, on daily or monthly basis, to determine how much water is available for use at any time. Inflow credit may differ by region – for example as a percentage of total inflow equal to the percentage of the pool allocated to the user in the East, or as specific water rights in the West. A user would not be restricted by the state of the reservoir pool as a whole, but rather only by the balance in its own storage account. Storage accounts are always accessible for use, which is why storage accounts are considered floating or vertical pools – the dam outlet can always reach them. However, for a diversion from the reservoir pool, it is feasible for the water level to drop below the user's withdrawal facility, making the account inaccessible in that way.

A-9. **Storage Accounts: Evaluating Yield in a Shared Conservation Pool**.

a. The methods described above to develop storage/yield relationships (computing either the storage requirement for a range of consistent water withdrawals, or the maximum consistent withdrawal for a range of storage capacities) have been demonstrated for evaluating entire reservoir pools. Often, the need is for the storage/yield relationship of a reservoir at a given site, or the specific yield of an existing reservoir with the storage allocation defined by its Guide Curve, and so this analysis is appropriate. In the case of M&I water supply at a multipurpose USACE reservoir, local water users seeking to supply a demand less than the yield of the full project have sought agreements to reserve some portion of the reservoir storage volume for their use. The determination of volume required for a single use from a shared Conservation Pool is similar to the storage/yield computation for the reservoir Conservation Pool as a whole but differs in the share of the storage space and inflow considered. A single user owning a portion of the Conservation Pool receives only a portion of the total inflow for their use. The simple yield analysis methods described in paragraph A-4 can be used to compute the required storage for a specified use, with the computation using the user's share of inflow rather than the total inflow. The iterative simulation method can be adapted the same way and allows much more detailed analysis of the reservoir and its operations. With the iterative simulation method, both the reservoir as a whole and the new user's “storage account” (or “water account”) are simulated, considering total inflow and the portion of inflow assigned to the storage account, with successive approximations used to determine the firm yield of a specified storage account volume.

b. The yield analysis for a shared Conservation Pool is more straightforward where the storage account of a user allocated a certain percentage of a reservoir pool is credited a certain percentage of the reservoir's available inflow. The situation is more complex if a user with a more senior water right is entitled to a larger or more reliable share of inflow than other users. However, once the share of inflow is defined, the procedure to compute storage requirement is the same from that point forward. For simplicity of the explanation and example computations, this document will focus on the former case, with users receiving the percentage of inflow equal to their percentage of the Conservation pool. (It is important to note that USACE does not have a national policy on how to compute a user's share of inflow.)

c. In these examples, it is assumed that the user's share of losses such as evaporation and leakage is also equal to the user's percentage of the pool capacity, and so the user receives a percentage of net inflow (equal to inflow minus losses). This important assumption should be the source of some discussion for a given analysis. The user has a share in a reservoir. Often the surface area of the inactive pool of that reservoir is large enough to cause the majority of the evaporation. Should a user with a share in the reservoir be charged proportionally for that evaporation? Or, if it currently has a very low balance in its storage account, should it be charged less of the total evaporation? In the latter case, the user would receive a percentage of inflow equal to its allocated percentage of storage capacity and lose a percentage of losses equal to its current percentage of storage volume. An argument for this latter assumption is that losing evaporation proportional to the percentage of storage capacity, rather than a percentage of current storage volume, could make a storage account go negative, as the user would continue to lose at the same rate, even with a low balance. An argument against the latter assumption is that a user that left its water in the reservoir while others removed theirs would then bear a larger proportion of the evaporation from the inactive pool.

d. Simulation of storage accounts is demonstrated using the same streamflow time-series used in paragraph A-6 to demonstrate varying time-intervals, shown in Figure A-14 having the storage/yield relationship shown in Figure A-15.

e. Figure A-22 shows a daily simulation of a 400 KAF reservoir, receiving inflow and releasing for a 1,371 cfs demand (firm yield), summarized as 3.4 cfs/KAF. The most critical period is 1953 through 1954. Figure A-23 shows the result of using only 200 KAF of the 400 KAF to meet the demand, with the 200 KAF "storage account" appearing as the green fill in Figure A-23. The maximum demand (firm yield) that can be met by the storage account is 685 cfs. The inflow available to the 200 KAF storage account is 50% of the total inflow, because the account volume is 50% of the total volume and is plotted as the darker blue line in Figure A-23, with total inflow as the lighter blue. The resulting maximum demand, or firm yield, turns out to be 50% of the total-pool firm yield of 1,371 cfs (still providing 3.4 cfs/KAF) with these simple assumptions. It is not common that the situation is actually this simple, but when it is, the result of computing yield of a portion of the Conservation Pool is a simple fraction of the firm yield of the total pool.

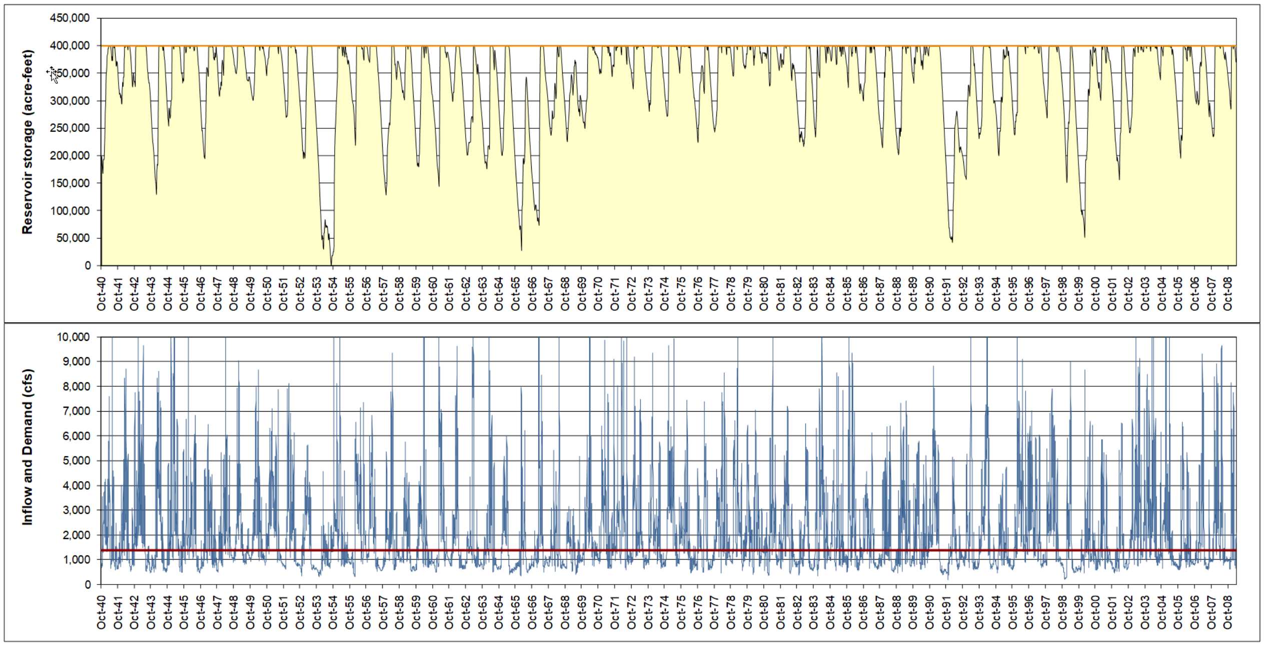

Figure A-22. Simulation of a 400 KAF reservoir with maximum demand (firm yield) equal to 1,371 cfs.

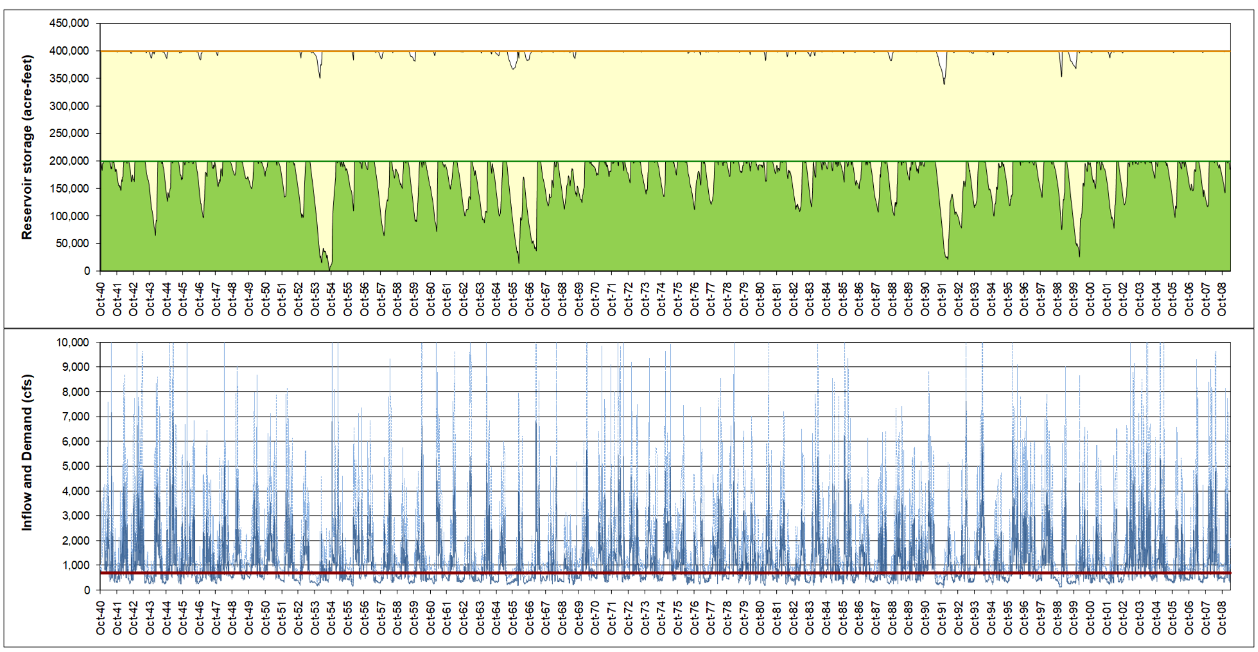

Figure A-23. Simulation of a 400 KAF reservoir with a 200 KAF storage account, firm yield of account equals 685 cfs.

f. In Figure A-23, the storage account which has capacity equal to half the total pool is plotted on the same axis as total reservoir storage, and so it appears as if it is at the bottom of the reservoir pool. This appearance is not intentional, and in fact the storage account described here is not a horizontal reservoir pool at all, but more like a vertical slice of the Conservation Pool, or perhaps a floating pool that can be reached from anywhere in the reservoir at any time. As long as a storage account has a positive balance, a user with access to the reservoir pool can withdraw water without overdrawing the account.

g. Figure A-24 shows the lower end of the storage/yield curve of Figure A-15, with the added lines showing the firm yield of storage accounts of various sizes, dedicating only part of the total pool to meeting demand. Looking at the upper right corner of the graph to where a storage volume of 400 KAF provides firm yield of 1,371 cfs, and following the red line down, 75% of that 400 KAF pool provides a yield of 1,028 cfs, and 50% of the pool provides a yield of 685 cfs, always providing 3.4 cfs/KAF. The red line for the 400 KAF pool spans from the original entire-pool storage/yield point to the origin. Additional lines in Figure A-24 trace reservoir sizes 200 KAF and 100 KAF, showing firm yield of the total pool on the original blue curve, and then the yield of portions of the pool as the pink and orange lines between the original curve and the origin. Reservoirs of 200 KAF and 100 KAF provide firm yield of 1,031 cfs and 793 cfs, respectively, for the total pool, and storage accounts in those pools provide 5.2 cfs/KAF and 7.9 cfs/KAF.

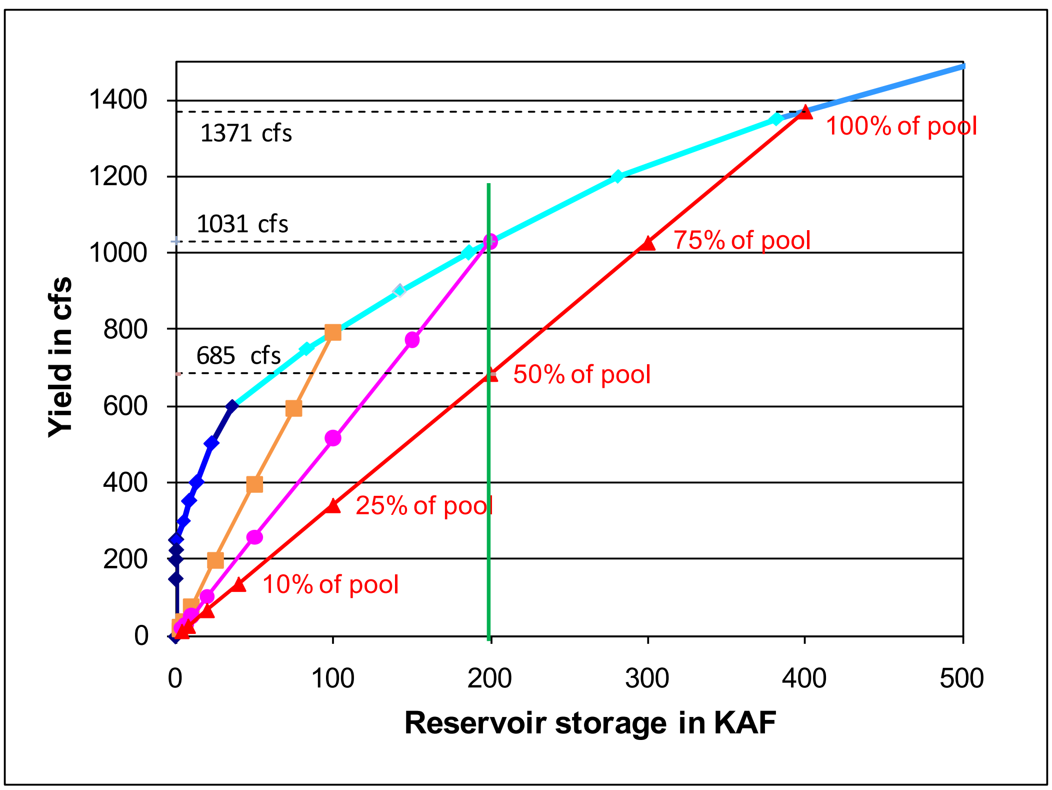

Figure A-24. Lower portion of storage/yield curve, demonstrating the yield values for portions of the reservoir pool.

h. An interesting comparison is seen when looking at the firm yield of a 200 KAF reservoir, which is 1,031 cfs, and comparing it to the firm yield of 50% of a 400 KAF reservoir, which is 685 cfs. The reason for the difference in firm yield of the same storage volume is that a 200 KAF reservoir dedicated to maximizing a consistent delivery can use all the inflow for that purpose, while 50% of a 400 KAF reservoir, defined as a 200 KAF storage account, can use only 50% of the inflow. As noted, Figure A-23 shows the simulation of the 200 KAF storage account within a 400 KAF pool (50% of the pool), with firm yield equal to 685 cfs, and for comparison, Figure A-25 shows the simulation of 100% of a 200 KAF pool, with firm yield equal to 1,031 cfs.

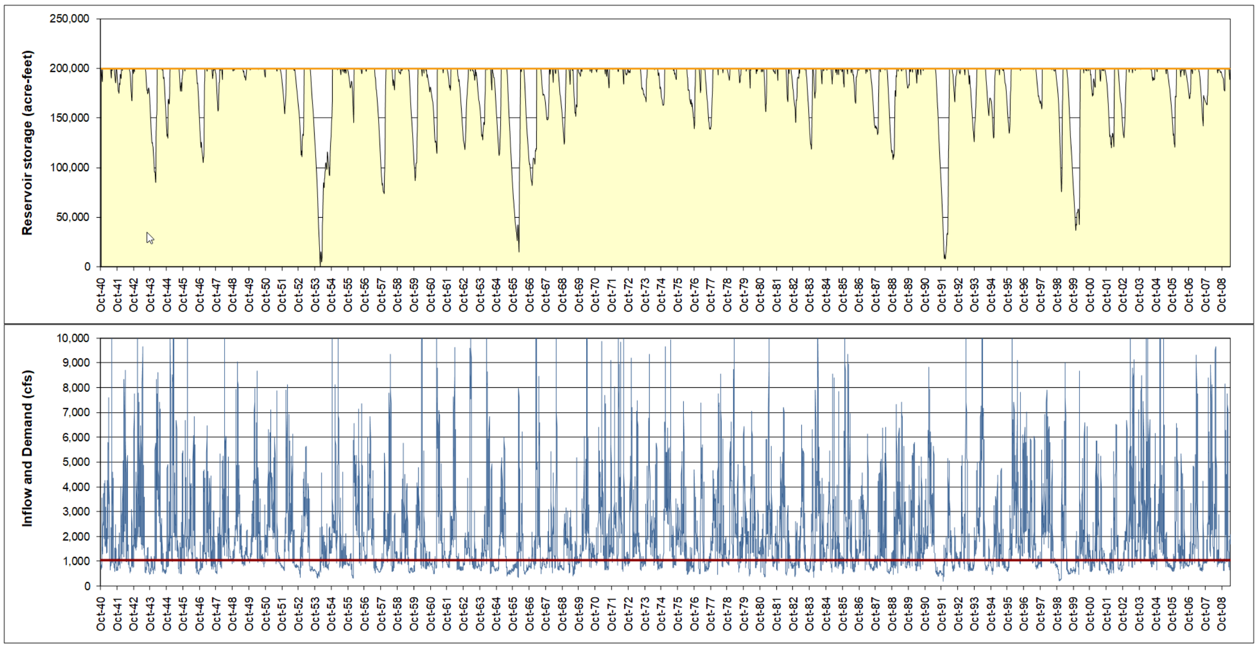

Figure A-25. Simulation of a 200 KAF reservoir where firm yield equals 1,031 cfs.

i. Storage Account Simulation with More Complexity.

(1) As noted in the previous section, the fact that the firm yield of 50% of a reservoir pool was equal to 50% of the firm yield of the entire pool suggests that a simple ratio can be used to determine the storage required to meet a demand that is less than the firm yield of the reservoir. In other words, it was found simply as a fraction of the full pool equal to the fraction of desired yield to the firm yield of the full pool. This straightforward result is sometimes accurate, but often the apportionment is not that simple. This section looks at storage accounts in reservoirs with more complex operations. The following sections contain the storage account example from paragraph A-9 with various complexities added, to show the impact of those complexities on reservoir firm yield. A 400 KAF reservoir with a storage account of 200 KAF is used throughout. The first complexity to be added is seasonally varying demand.

(2) Variable Demand.

(a) Often more water is needed during seasons when less water is available from the stream. Figure A-12 above showed how the firm yield decreased from assuming a constant diversion to assuming a seasonally varying diversion in the simple example. Following from Figure A-23, showing a 400 KAF reservoir with a 200 KAF storage account, Figure A-26 changes the demand from constant to varying throughout the year, as defined in Figure A-27. The firm yield of the storage account decreases from a constant 685 cfs to an annual average of 667 cfs with this change. Figure A-28 shows the impact of varying demand (with this pattern) on the initial storage/yield curve, with the dashed curve representing variable demand. Note: There is little change in the curve below a firm yield of 500 cfs.

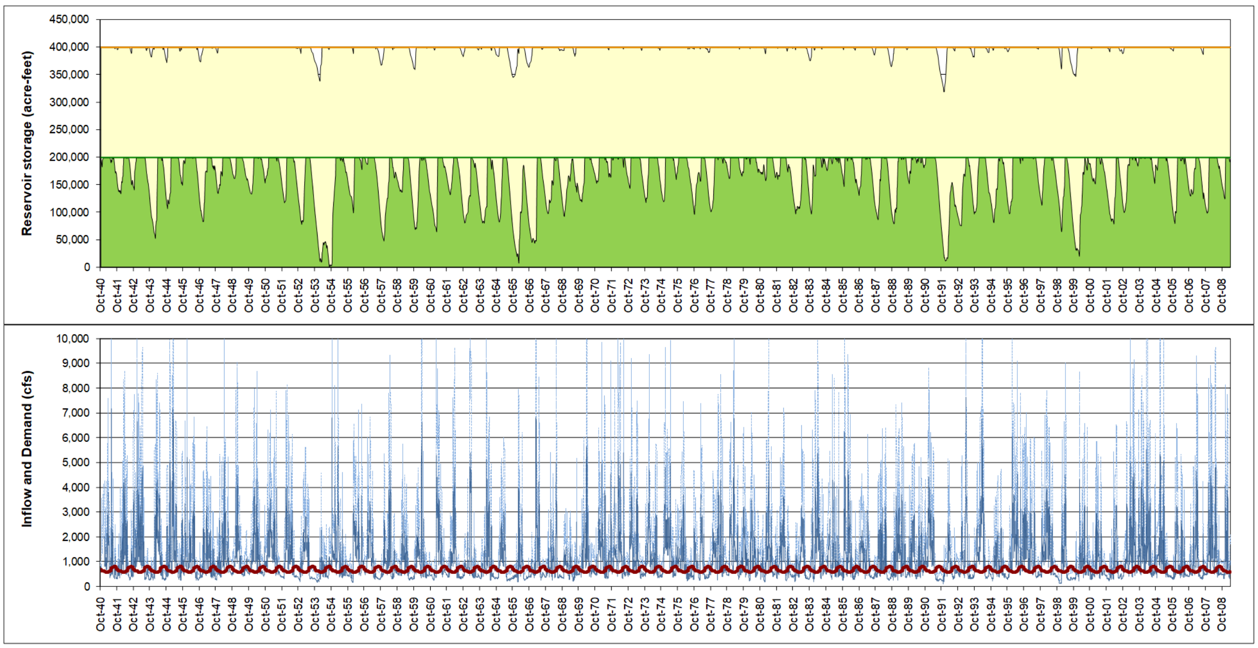

Figure A-26. 400 KAF reservoir, 200 KAF storage account, varying demand, average firm yield equals 667 cfs.

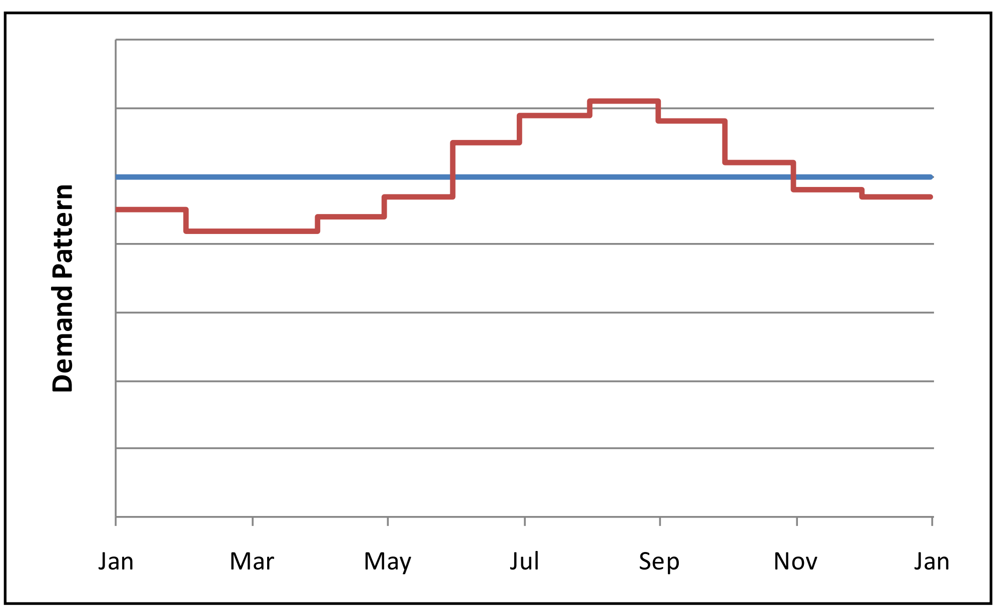

Figure A-27. Pattern of monthly varying demand.

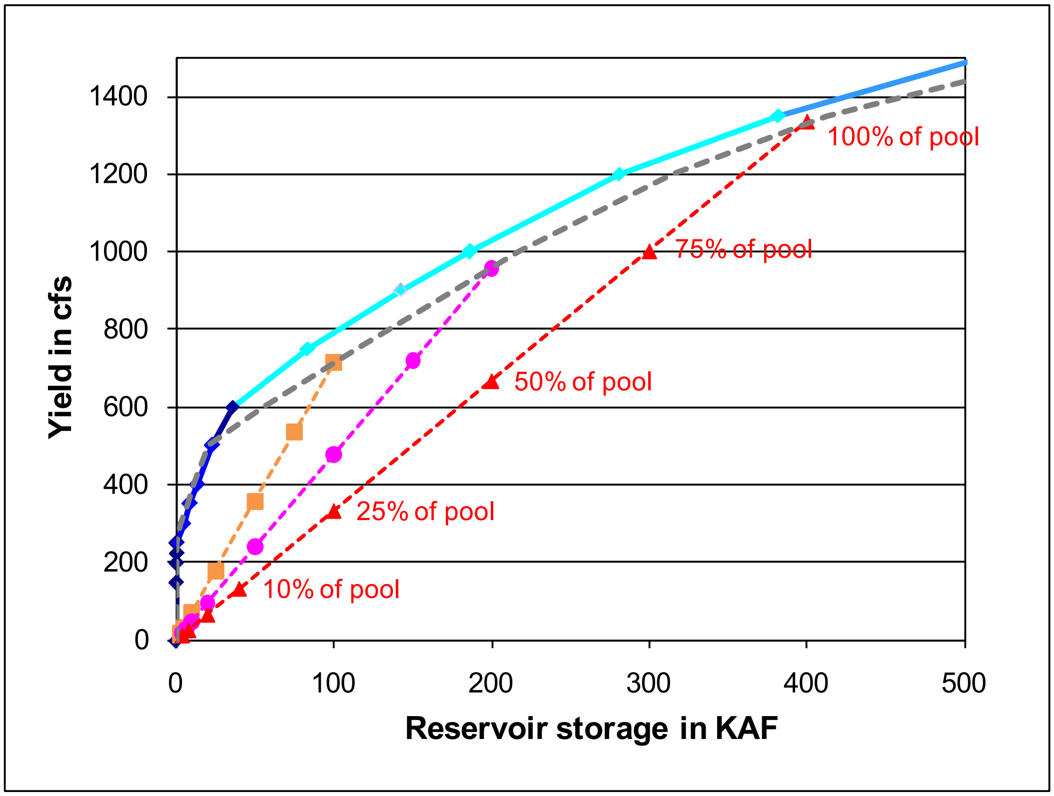

Figure A-28. Storage/yield curves with monthly varying demand (dashed lines).

(3) Surplus Inflow.

(a) Notice in Figures A-23 and A-26 that the storage account represented by the green fill is often low during times that the reservoir itself is near or at the Guide Curve, representing a full Conservation Pool. In this simple example of a reservoir operating for water supply yield and perhaps recreation, there is no other user removing water from the reservoir, as the recreation user would choose to store its inflow to maintain pool elevation. When the reservoir is full (at Guide Curve), the non-water-account portion of the inflow becomes surplus and could perhaps be made available to the storage account. If there were other users, each with a storage account, this accounting for surplus inflow would occur between storage accounts as well (with all accounts sharing surplus, and full accounts providing surplus to others) but in this simple example, surplus is defined as the inflow arriving when the reservoir is already full.

(b) Figure A-29 shows the constant demand case where the 200 KAF storage account receives the surplus inflow available when the reservoir is full. Firm yield increases from 685 cfs to 720 cfs, as compared to Figure A-23. Notice that the storage account's share of inflow (shown as the dark blue line) is now often equal to the total inflow, and the storage account drafts are only during times that the reservoir is not full and the account is not receiving surplus inflow. (The green storage account only drafts when the yellow total reservoir storage drafts.) Figure A-30 shows the variable-demand case accounting surplus inflow, and the yield has increased from 667 cfs to 692 cfs due to the surplus.

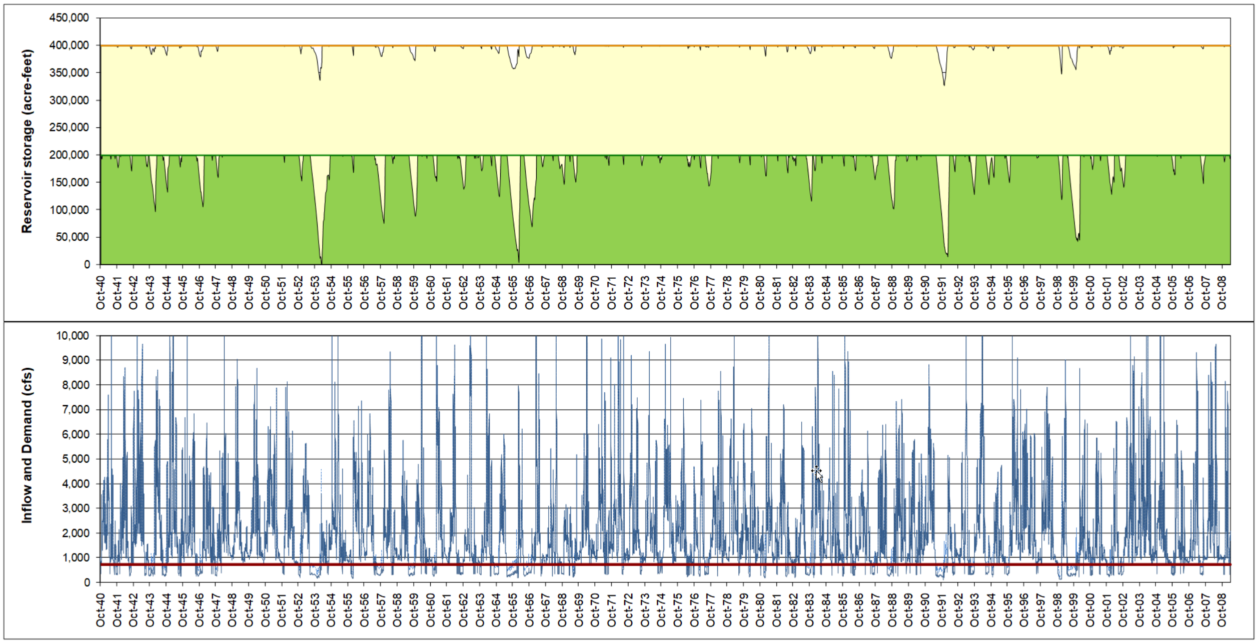

Figure A-29. 400 KAF reservoir, 200 KAF storage account receiving surplus inflow, constant firm yield equals 720 cfs.

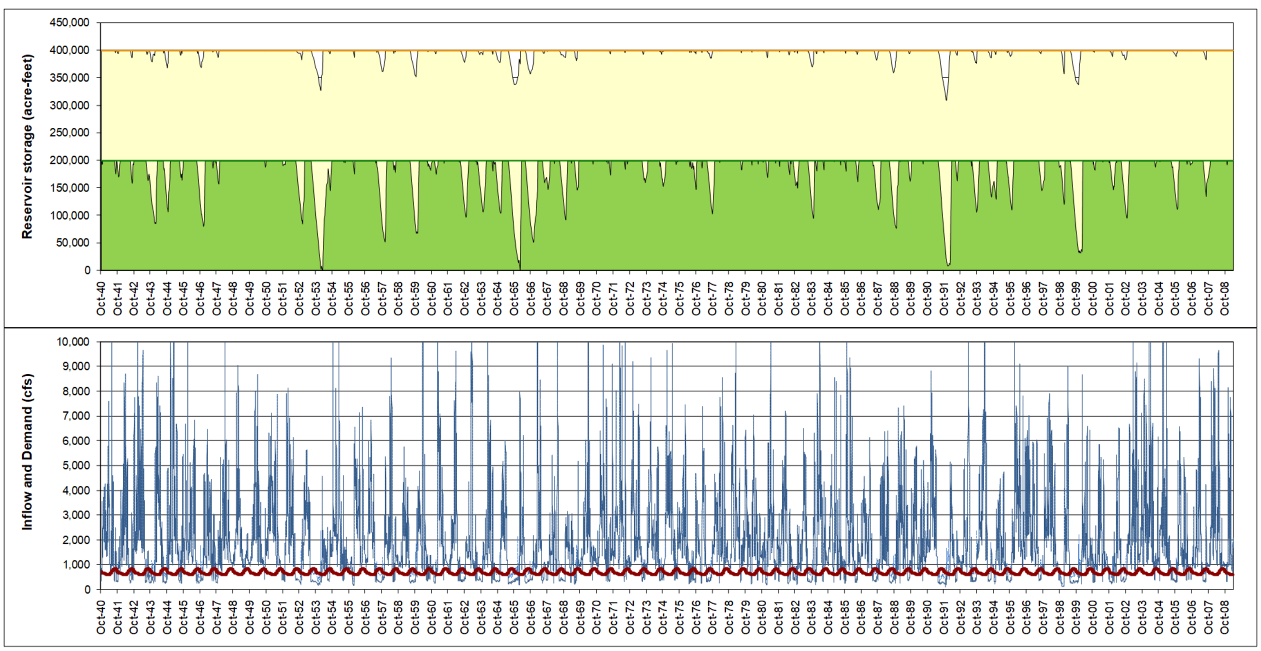

Figure A-30. 400 KAF reservoir, 200 KAF storage account plus surplus inflow, variable firm yield averages 692 cfs.

(4) Seasonally varying Guide Curve.

(a) The next complexity to be added to the storage account example is a seasonally varying Guide Curve, creating flood storage space during high flow times, and a limited downstream channel capacity defining use of that space. In this example, although the Guide Curve defining the size of the Conservation Pool varies, the storage account capacity does not. Figure A-13 in paragraph A-4b demonstrates that a variable Conservation Pool, reduced during some times of the year, has a smaller yield than a pool always at the largest size. To start the comparison, refer first to Figure A-29, which shows a 400 KAF reservoir with a constant Guide Curve, having a 200 KAF storage account receiving 50% of inflow (plus surplus) producing 720 cfs of firm yield. Figure A-31 adds the effect of the reservoir having a seasonally varying Guide Curve that reduces the Conservation Pool to 300 KAF during the flood season, and still releasing 720 cfs (i.e., demand is not maximized). With this change, the 720 cfs release for yield does not fully draft the storage account, meaning the firm yield is greater in this situation, rather than less. This result is at first quite surprising, and there are several reasons for it. First, during the times the Guide Curve is low, creating a Flood Pool, the 200 KAF storage account is a larger percentage of the remaining Conservation Pool, and so receives more of the inflow, i.e., the account is 67% of the Conservation Pool when the Guide Curve is at 300 KAF, rather than 50%. Usually, this larger share of the inflow happens during the high flow season when storage account and reservoir are full, but since the 1953 through 1954 critical period spans a high flow season, the storage account is now more able to recover during that time with its larger share of inflow. The result of this recovery is a slightly shorter critical period that does not fully draft the account. (Note: In some cases a contract might specify a percentage-of-pool that applies all year, and this situation would not occur.)

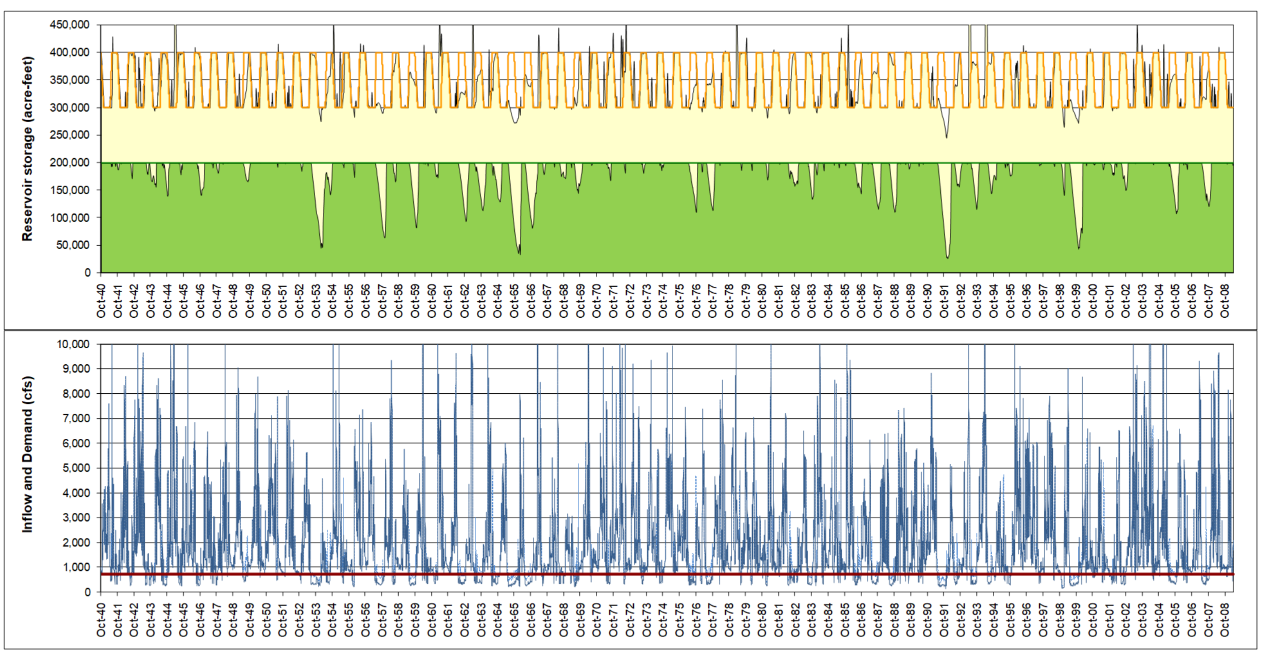

Figure A-31. 400 KAF reservoir, variable guide curve, 200 KAF storage account plus surplus, demand equals 720 cfs.

(b) Additionally, Flood Pool drawdown sometimes coincides with the reservoir draft due to use during low inflow. At those times, the lowering Guide Curve "fills" the reservoir by bringing the Guide Curve down to the actual reservoir level, and so introduces surplus inflow for the storage account, making the storage account benefit from the decreasing Guide Curve. Maximizing the demand for this variable Guide Curve, the firm yield of the 200 KAF storage account has increased from 720 cfs to 765 cfs, shown in Figure A-32. Note that, while 1953 had been more critical than 1965 by only a slight amount with the flat Guide Curve in Figure A-29, 1965 through 1966 has become the critical period with the variable Guide Curve and surplus inflows. This change happens because the dry period starts earlier in 1965 than 1953, not allowing the reservoir to fill when the Guide Curve is high. In 1953, the simulation shows the reservoir filling, and so providing some surplus inflow to the storage account during drawdown. Figure A-33 shows the variable Guide Curve and surplus inflow operation for both critical periods. In the absence of the "surplus inflows" assumption, 1953 remains the critical year, as seen in Figure A-34, with firm yield equal to 761 cfs. Note the surplus inflows provided only an additional 4 cfs of firm yield when the variable guide curve is included, since the 1965 through 1966 critical period did not benefit from surplus inflows because the reservoir was not full during this time. Note in Figures A-33 and A-34 that the inflow belonging to the storage account is the dark blue line, and the total inflow is the light blue line. Providing surplus inflow to the storage account made a dramatic difference in this simple case when the GC was constant and the reservoir was full during some of the critical period. But introducing the variable Guide Curve, which allows the storage account a higher percentage of inflow in the winter wet season, made the surplus flows much less influential to the firm yield.

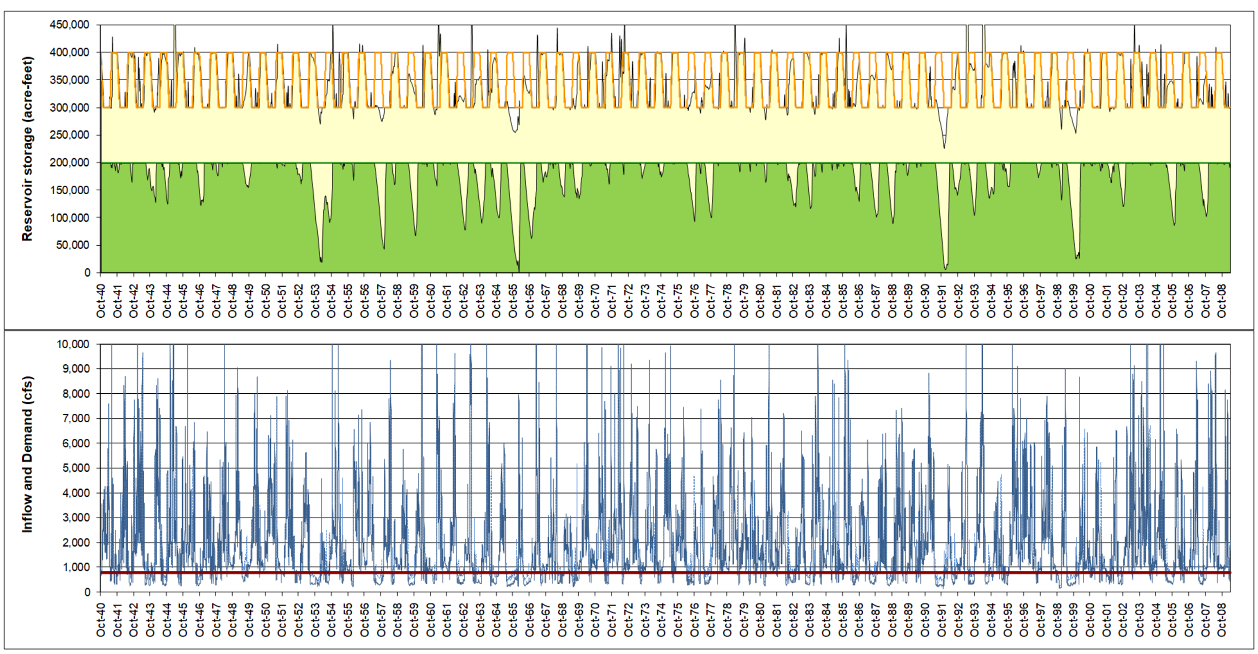

Figure A-32. 400 KAF reservoir, variable guide curve, 200 KAF storage account plus surplus, firm yield equals 765 cfs (1953).

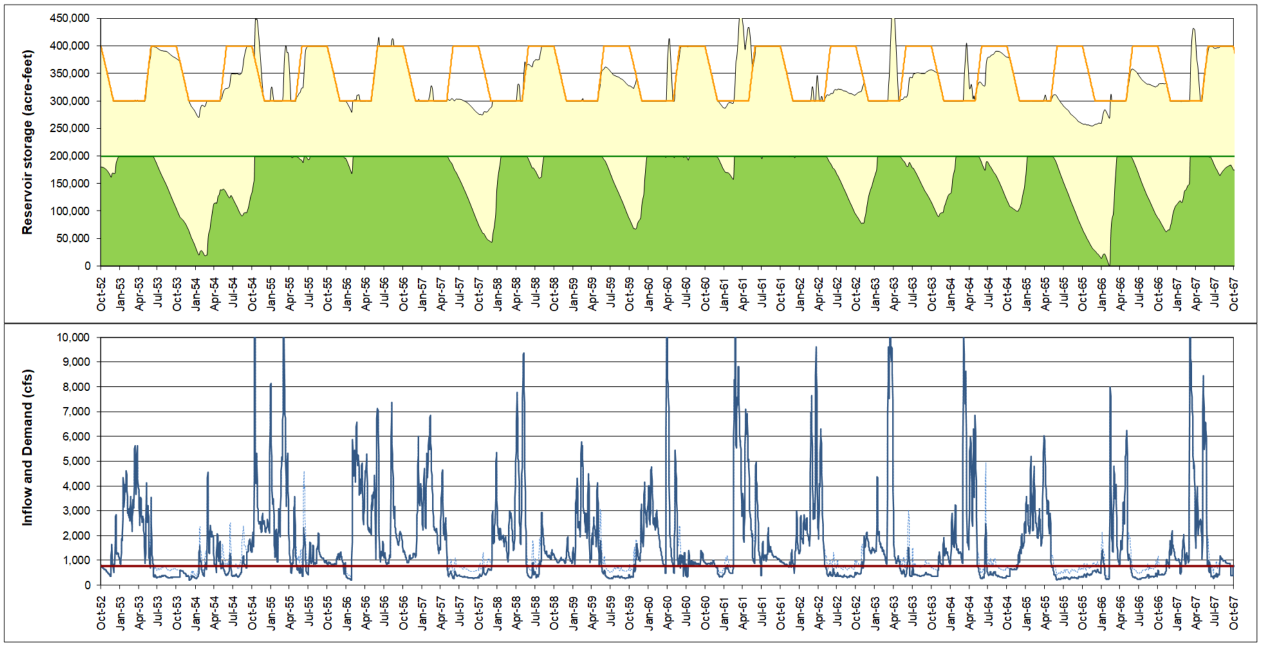

Figure A-33. 400 KAF reservoir, variable guide curve, 200 KAF storage account plus surplus, firm yield equals 765 cfs (both critical periods).

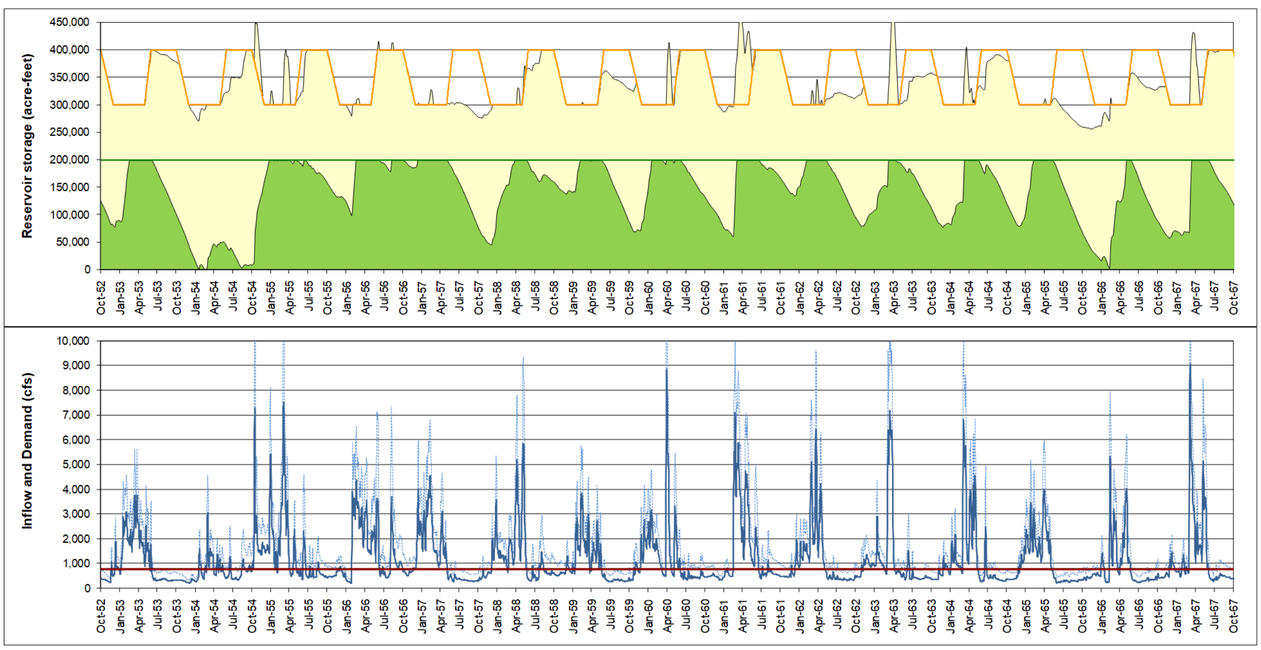

Figure A-34. 400 KAF reservoir, variable guide curve, 200 KAF storage account not receiving surplus, firm yield equals 761 cfs (both critical periods).

(5) There are many more potential complexities in storage accounting than have been demonstrated here. Determination of the size of storage account required to produce a desired firm yield would need simulation of all relevant complexities, and might be quite involved. A storage accounting ability has been added to HEC-ResSim that considers the complexities

discussed here, and will allow further details defined by the user. Note that in ResSim, the term water account is used, and has the same meaning as storage account.

A-10. **Reliability of Firm Yield**.

a. The customary description of the “safe yield” or “firm yield” of a water system, for any type of yield (water supply, hydropower, flow augmentation), is the maximum delivery rate that could have been supplied at a location throughout the observed period of record. The most challenging or “critical” periods for this evaluation are the driest periods of the record, although the most critical dry period might differ based on the demand and storage volume in question. A small storage that refilled each year would find a single very dry year most critical, whereas a larger storage can sustain use through the single very dry year and would be more challenged by a succession of somewhat dry years.

b. Defining “firm yield” as supplying demand without failure (100% reliability) during the observed period of record is a straightforward definition, but it does not address the reliability of satisfying that demand in the future and the likelihood of drier periods causing shortage. Adding some factor of safety or buffer to a storage requirement is common, but not well defined in terms of the reliability it provides. One can perhaps estimate the return period of the critical drought and estimate annual reliability (or instead the probability of failure or shortage) as the inverse of the return period. However, as with estimates of floods with large return periods, there is a great deal of uncertainty in estimating longer return periods. When dealing with droughts, the difficulty of duration is added, as the return period of the driest single year of a drought will not be the same as the return period of the driest 2 years, or driest 3 years, etc. An analysis of flow volume or deficit is needed for many drought durations, and the duration that is critical to the reservoir system being studied must be chosen to define the actual return period of the critical drought.

c. The following paragraphs describe several methods of defining the reliability of yield estimates for a given period of record of streamflow. Reliability is in some cases annual, and in some cases refers to a longer period.

d. Drought of Specified Return Period.

(1) An effort can be made to define a critical dry period that has a particular return period, to then compute firm yield or storage requirement having a failure probability that is the inverse of that return period. An example of an approach referred to as non-sequential mass curve analysis, described in USACE, 1975, is shown here using the 41-year time series from paragraph A-4, Figure A-2. Figure A-35 displays the frequency analysis of independent low flow events for various durations, from one to 72 months. As described in USACE, 1975, the plotting position (estimate of non-exceedance probability) of the smallest event is defined in equation A-5:

$$PP_1 = 1 - 0.5^{1/N} \qquad \text{(A-5)}$$

with N equal to number of years minus duration, with the plotting positions of less severe events increasing by that increment. The 1976 through 1977 period was the driest in the 41 years for durations between six months and 24 months, offering non-exceedance probability near 1.8%; however for 12 and 18 months, that period's volume plots near 1% on the estimated frequency curves. The later 1987 through 1992 critical period was the driest in the 41 years for durations between 36 months and 72 months, offering non-exceedance probability near 2%; however on the estimated frequency curves, the critical 36-month volume plots near 3%, and the 72-month volume plots near 0.5%.

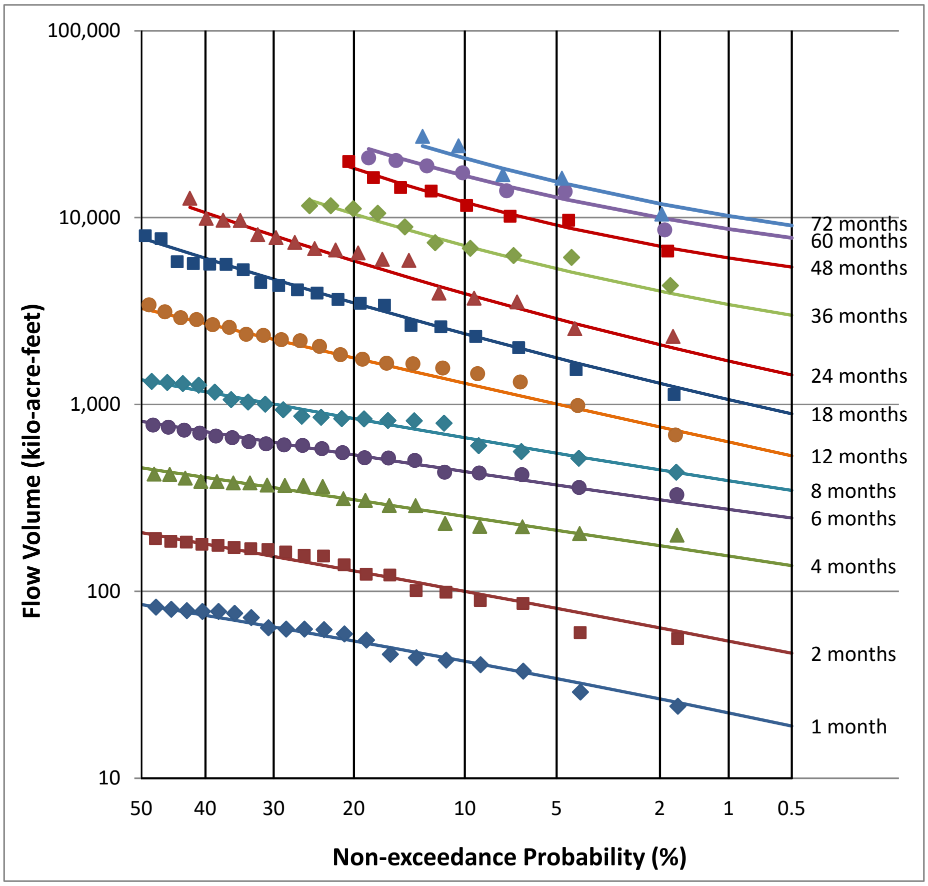

Figure A-35. Frequency analysis of independent minimum flow volumes of various durations.

(2) Figures A-36 through A-38 contain non-sequential mass curves for 1% annual chance of shortage (1% non-exceedance probability) and 2% annual chance of shortage, or return periods of 100 years and 50 years, respectively. Unlike the Rippl Mass Diagram of paragraph A-4, these mass curves are not the accumulation of a time-series of flow, but rather individual estimates of the total flow volume for each duration having the specified probability of non-exceedance. A curve is drawn connecting the estimates only to allow interpolation to unspecified durations. Like the Rippl Mass diagram, a cumulative demand curve is also plotted. The point of tangency between the mass curve and the straight demand curve identifies the duration which is critical, and the difference between supply volume and demand volume at that duration defines the storage requirement.

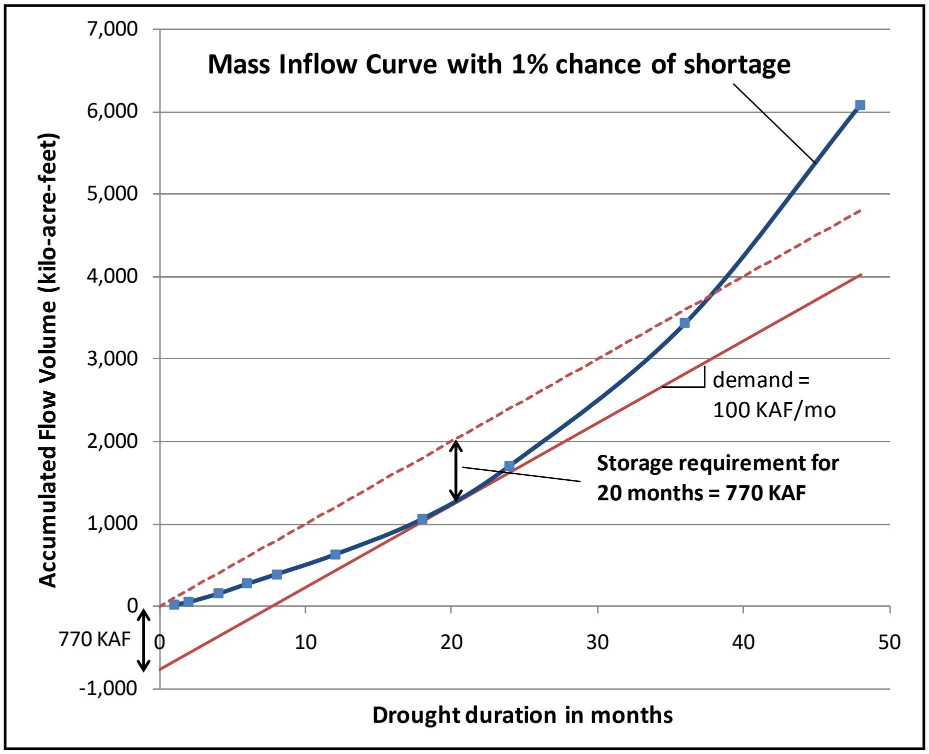

Figure A-36. Non-sequential mass curve for 1% annual chance of shortage, demand equals 100 KAF/month.

(3) In Figure A-36, for the 1%-chance non-exceedance, or 100-year return period, the storage requirement for a demand of 100 KAF/month is 770 KAF at a critical duration of 20 months. In Figure A-37, a demand of 200 KAF/month is also included, showing a storage requirement of 3,780 KAF at 38 months. Finally, in Figure A-38, the 2%-chance or 50-year mass curve is displayed. For the 50-year return period, a demand of 100 KAF/month shows a storage requirement of 520 KAF with a critical duration of 16 months, and a demand of 200 KAF/month shows a storage requirement of 3,150 KAF in 36 months. Recall from paragraph A-4 that that analysis of the 41-year period of record showed that the May 1976 through December 1977 critical period required storage volume of 669 KAF to supply 100 KAF/month, and the June 1986 through April 1995 critical period required 4,068 KAF to supply 200 KAF/month. This non-sequential analysis implies that the 1976 through 1977 critical period has between a 50- and 100-year return period, as the 669 KAF is between the 520 KAF from the 50-year curve and 770 KAF from the 100-year curve with similar duration. This conclusion is consistent with the non-exceedance probabilities inferred for that critical period from the frequency analysis shown in Figure A-35. A similar implication that the 1986 through 1995 critical period has a greater than 100-year return period, because its 4,168 KAF storage requirement is greater than 3,780 KAF from the 100-year curve, cannot be made, as that critical period lasted over six years and this analysis provided storage requirements for 200 KAF/month for critical durations near three years. However, the frequency analysis (Figure A-35) did show the critical period as having 0.5% non-exceedance (200 year return period) for the 72-month duration.

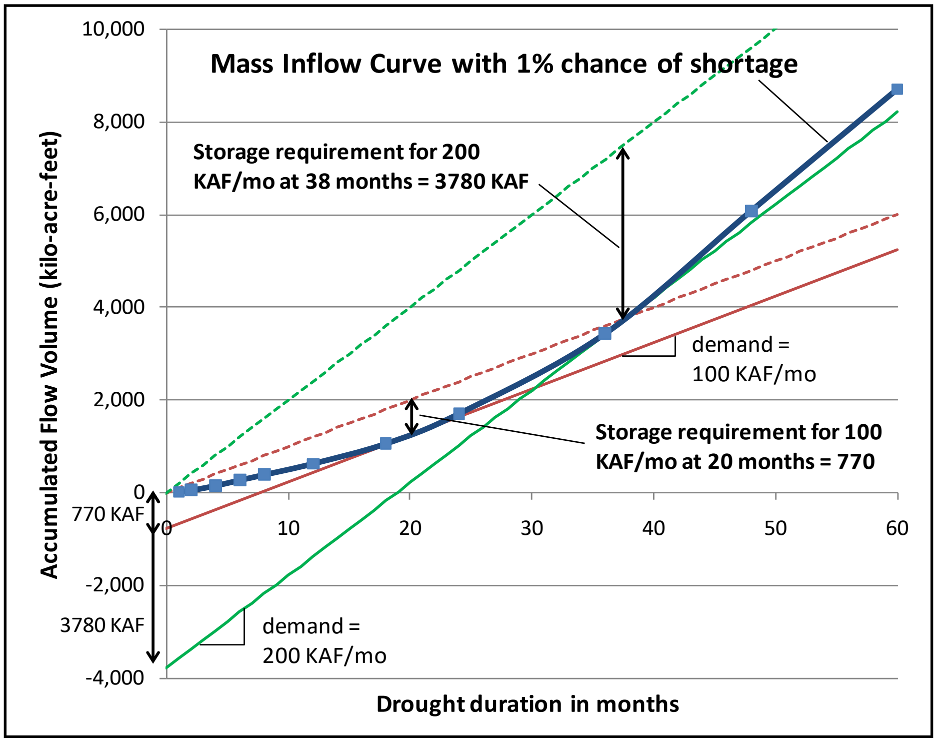

Figure A-37. Non-sequential mass curve, annual 1% chance of shortage, demand equals 100 and 200 KAF/month.

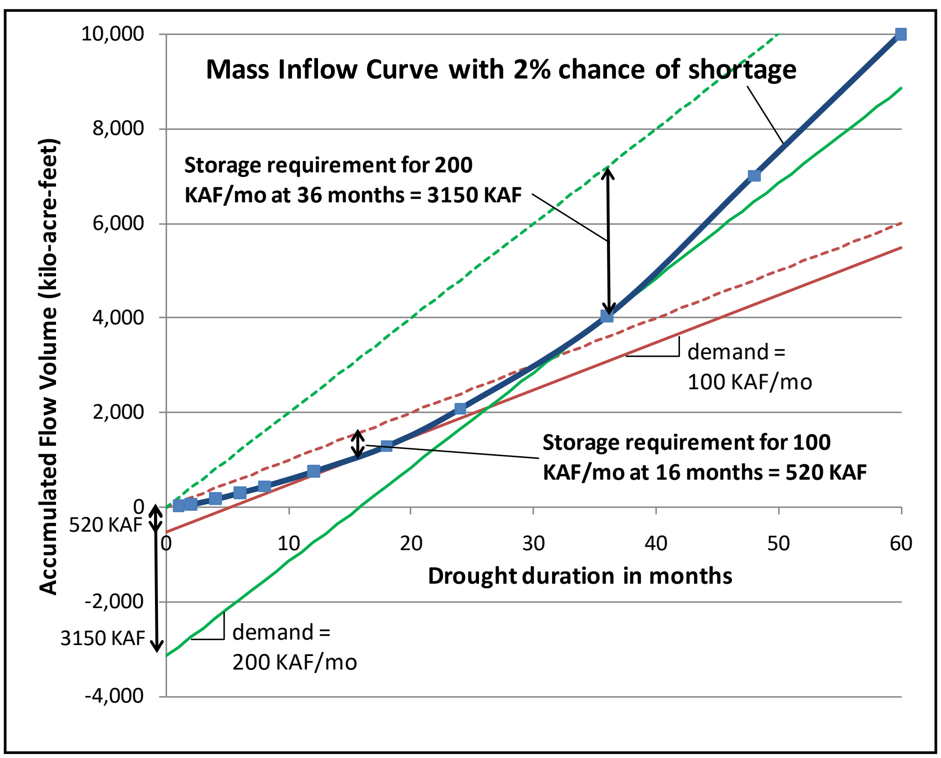

Figure A-38. Non-sequential mass curve, 2% annual chance of shortage, demand equals 100 and 200 KAF/month.

(4) There are some shortcomings to the non-sequential mass curve approach. One problem is that durations longer than one year blend wet periods and dry periods. Finding the storage requirement for a critical duration does not recognize the fact that a critical period could be one dry period, or could perhaps be two dry periods and the wet period between them, or even a longer series of wet and dry periods. Instead, the computation just considers the total volume for that duration, and in effect assumes it arrives at a constant average rate. The resulting storage requirement thus does not result from routing a reasonable wet-period/dry-period hydrograph through a reservoir or mass-balance to evaluate within-year storage. This approach is therefore more suited to within-year storage requirements for reservoirs small enough to fill each year.

(5) A possible extension of this non-sequential approach would define synthetic multi-year balanced drought hydrographs using the frequency analysis in Figure A-35 and the resulting duration-volumes for a specified annual non-exceedance probability. For example, a historical year could be scaled to the 1%-chance 12-month volume. A simulation analysis with that year-long hydrograph (perhaps with a normal year before and after) could determine the storage requirement for a given demand for a 1-year dry period. A second year could then be added after the first, and scaled such that the 24-month volume equaled the 1%-chance 24-month volume (meaning the second year's volume would equal the 1%-chance 24-month volume minus the 1%-chance 12-month volume). A simulation analysis with that 2-year-long hydrograph (again with a normal year before and after) could determine the storage requirement for a given demand assuming a 2-year drought. Additional years could be scaled and included in this way to create longer multi-year dry periods that maintained the 1% non-exceedance volumes as well as a reasonable flow time-series, computing storage requirements for each. The duration of drought that produced the largest storage requirement would be considered the critical duration. An implementation of this approach for 1%-chance volumes found a storage requirement of 601 KAF required to meet demand of 100 KAF/month for a 12-month dry period surrounded by wet years. This storage is smaller than the 770 KAF suggested by the non-sequential mass curve, most likely because the 12-month period is less than the mass curve critical duration of 20-months. Repeating with a 24-month dry period produced a storage requirement of 726 KAF, and a 36-month period produced a requirement of 819 KAF. All longer dry periods suggested 819 KAF, implying a critical duration of 3 years.

e. Reliability Methods based on Stochastic Streamflow Generation.

(1) The difficulty in defining reliability of reservoir yield is to some degree due to the limited record of streamflows available, providing a small sample of droughts. Methods exist for generating synthetic series of random streamflows that maintain the statistical characteristics of the original streamflow record. Added synthetic years of hydrologic record can provide more examples drought periods to evaluate, at the frequency with which they would occur. Two methods of yield analysis that utilize synthetic streamflows are of interest.

(a) Firm yield with specified annual reliability. The first method uses synthetic streamflows to develop yield estimates with defined annual reliabilities. After generating a long synthetic record of perhaps 1,000 years, a firm yield is found for a given storage that allows shortages in some percentage of the years. For example, a firm yield with 99% annual reliability would experience shortage in 10 of 1,000 years. With this approach, a storage/yield relationship may be generated for various annual reliability levels.

(b) Firm yield reliability for N-year project life. A second method using synthetic streamflows defines a probability distribution around the firm yield estimate for some specified project life (N years). It involves generating many synthetic records that are each N years in length, and for a given storage volume computing the firm yield for each record. When repeated 1,000 or so times as a Monte Carlo simulation, this technique describes the firm yield as a probability distribution. The firm yield with a non-exceedance probability of 10% has a 90% reliability over the N-year project life. (Note: This is not an annual reliability; because the annual flow volumes are not independent of one another, annual reliability cannot simply be computed with a binomial distribution.)

(2) Both of these approaches depend on the generation of a synthetic series of random streamflows. A common method for generating random annual flow volumes is a lag 1 autoregressive model (AR(1)). Those annual flow volumes are then disaggregated to monthly flow volumes. A simple method of disaggregating annual to monthly flows is a bootstrap approach that re-samples monthly patterns from historical years and then combines the selected pattern with a randomly generated annual flow volume. The two approaches that make use of synthetic streamflows described above are demonstrated using a simple iterative mass-balance simulation firm yield analysis from Paragraph A-4. This simplified computation was chosen to decrease the overall time for the analysis. However, these approaches are feasible with the iterative simulation method as well, to develop more accurate firm yield estimates. Disaggregation to daily rather than monthly flow might be required.

f. Firm Yield with a Specified Annual Reliability.

(1) The method described in paragraph A-10.e.(1)(a) is demonstrated using the same 41-year streamflow series used in paragraph A-4 to demonstrate simple yield techniques, shown as annual volumes in Figure A-39. Given the base10 logs of the annual streamflow volumes, with a serial correlation coefficient of 0.24 as well as the mean, standard deviation and skew, an AR(1) model with a Pearson Type III error distribution was used to generate random annual flows. Figure A-40 is an example of 100 generated years displaying some examples of drought periods that differ from the actual series. Figure A-41 contains 1,000 randomly generated years, which contains even more examples of possible drought periods, some more severe than the original record, as expected in a sample size of 1,000 years. Figure A-42 shows five patterns of the annual volume percentage by month, chosen randomly for each year to disaggregate the 1,000 annual volumes to monthly volume.

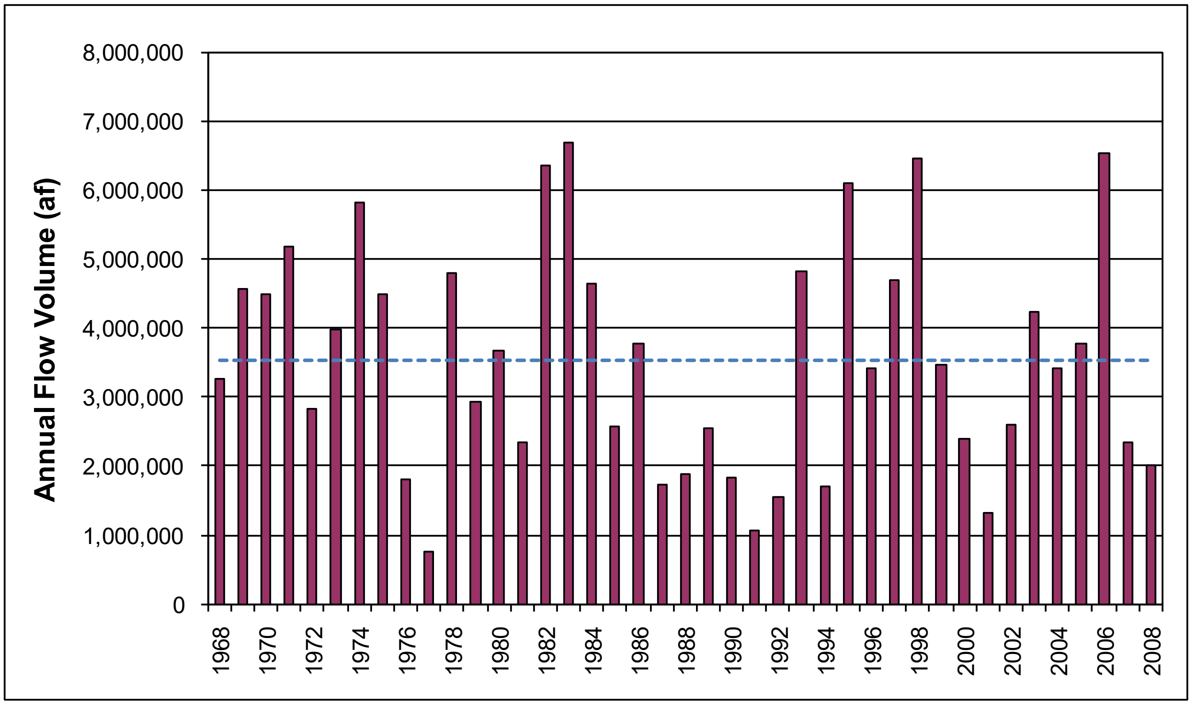

Figure A-39. Time-series of annual flow volumes from Paragraph A-4, Figure A-2, including average annual flow.

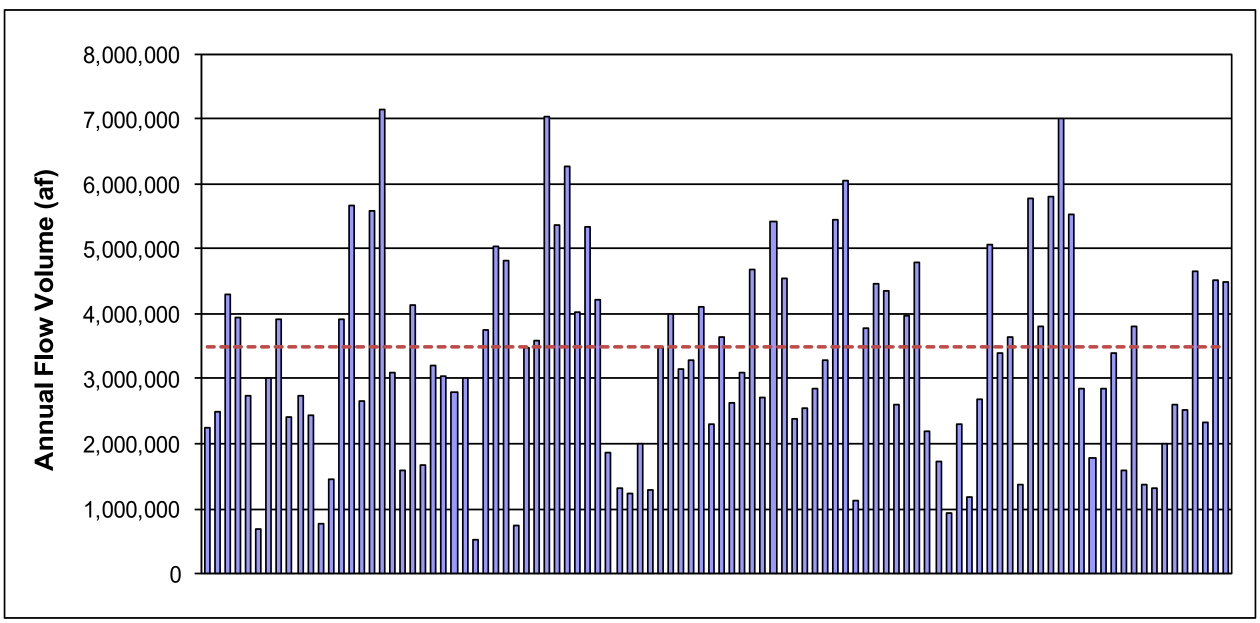

Figure A-40. 100 years of synthetic streamflow, developed as AR(1) of log10 flow volume.

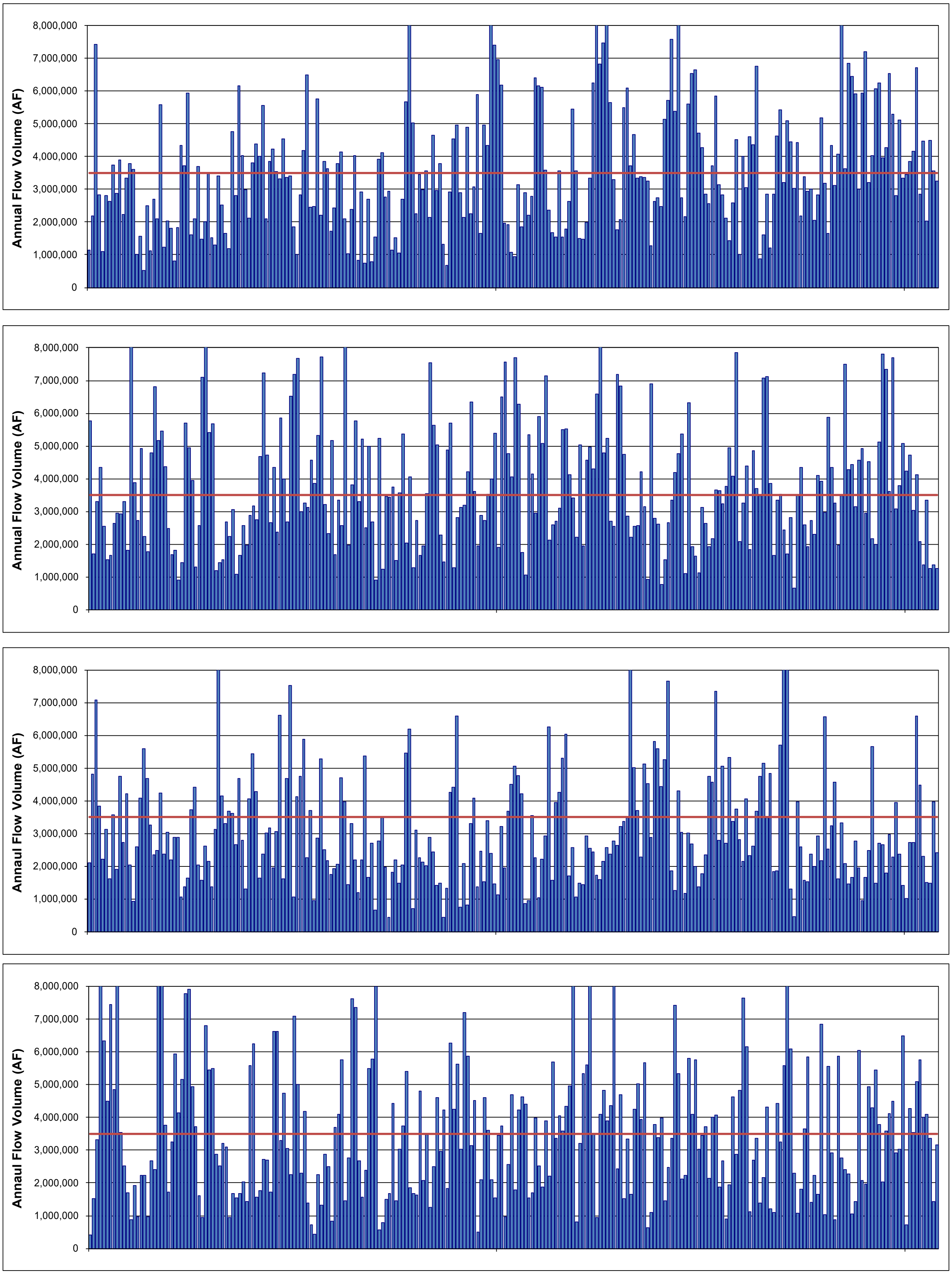

Figure A-41. 1,000 years of synthetic streamflow, developed as AR(1) of log10 flow volume.

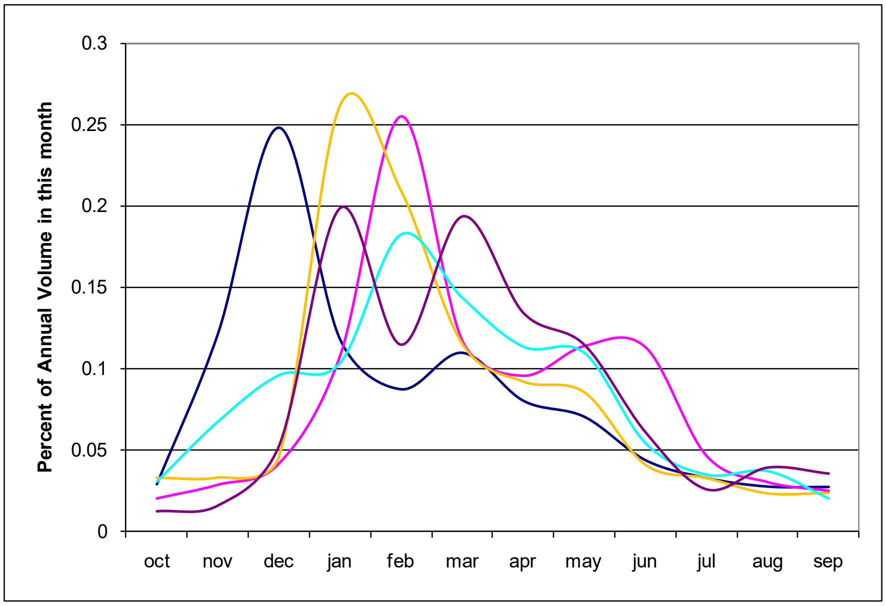

Figure A-42. Five patterns of annual volume by month, randomly chosen to disaggregate annual volume.

(2) As stated, the 1,000-year record of Figure A-41 was disaggregated into a monthly record (randomly choosing one of the five actual monthly flow patterns for each year), and a simple iterative reservoir simulation was performed. Reliabilities between 95% and 100% were defined by the number of failures in 1,000 years (e.g., 99% reliability is 1% failure and so has ten failures in 1,000 years). Failure was counted by year, with a year failing if any month failed.

(3) Figure A-43 shows the storage trace of the simulation meeting demand of 100 KAF/month (about one-third of the average annual flow), finding the storage volume that allows one failure year in 1,000 years, representing 99.9% annual reliability. That storage volume was 1,169 KAF, compared to the 669 KAF found by meeting demand without fail in the original 41-year record. (Note that the smallest volume that provides one failure brings the simulated storage volume to exactly empty in another year, not failing to meet demand in that year.) Figure A-44 shows a similar simulation, finding that ten failures in 1,000 years of providing 100 KAF/month requires a storage volume of 764 KAF, representing 99% annual reliability. This value is similar to the 669 KAF of the original 41-year record. Figure A-45 shows the relationship between annual reliability and storage requirement for the demand of 100 KAF/month. Obviously, to maintain a higher annual reliability requires more storage, and less storage will allow occasional but increasingly common failures, producing lower reliability. The 669 KAF storage requirement from the original 41-year record is noted on Figure A-45, with about 98.7% annual reliability. Figure A-46 shows the full storage/yield curves for this location, including the curve based on the original 41 years, and curves for both 99% and 99.9% annual reliability. The 99% reliability curve comes quite close to the original curve in two places, at 100 KAF/month and 225 KAF/month. There is one close point for each critical period in that record. One could interpret the closeness as showing that the critical periods in that record were perhaps more severe than might be expected for the 41-year record length, with return period near 100 years. Figure A-47 adds a curve for 90% reliability to Figure A-46. The fact that the 90% reliability curve is higher than the original 41-year curve implies that annual reliability for

the original curve is greater than 90%, at least as far along the curve as 250 KAF/month from 7,500 KAF of storage.

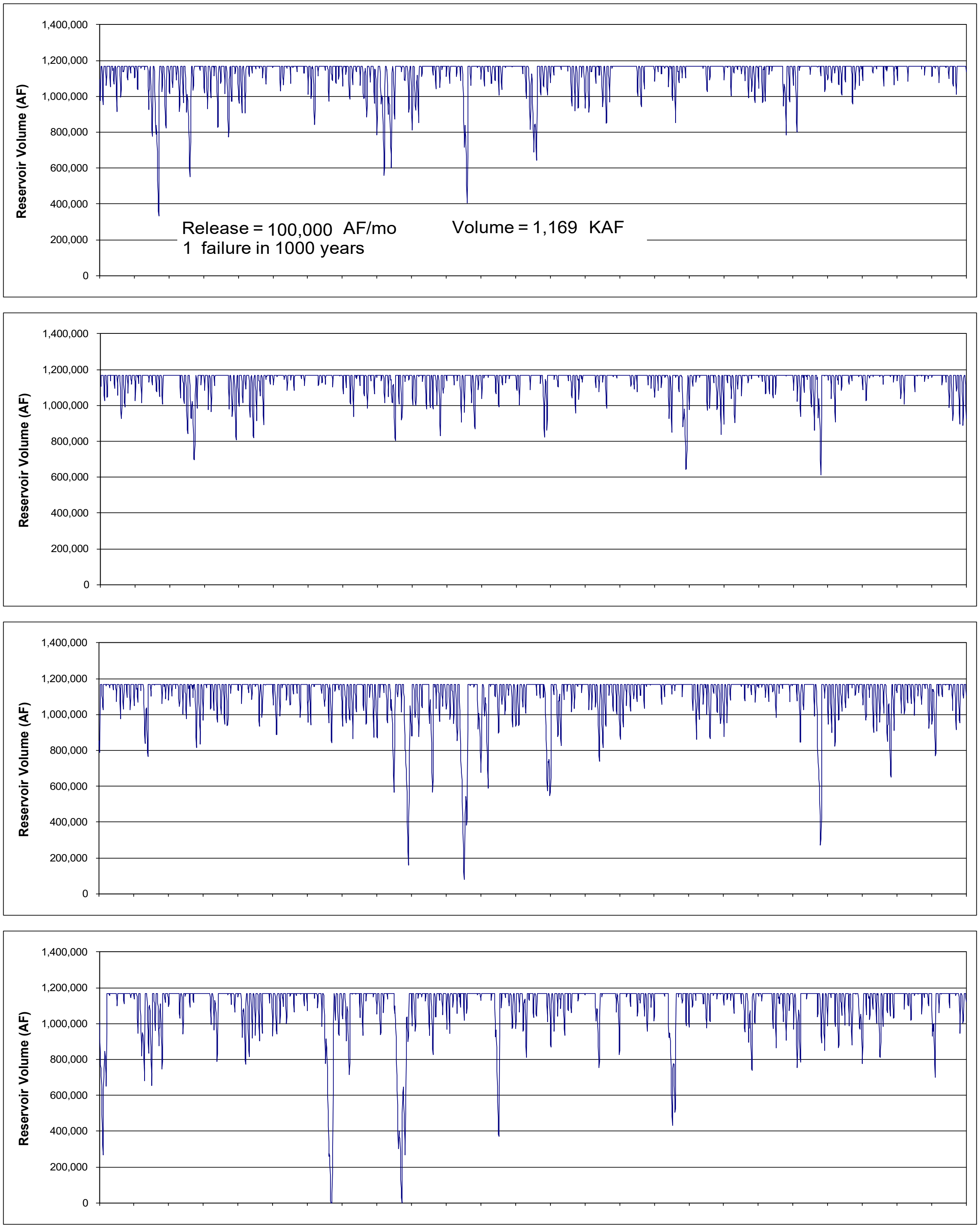

Figure A-43. Storage trace from a monthly 1,000-year simulation, finding storage capacity providing one failure in 1,000 years (99.9% reliability) for a demand of 100 KAF/month. Required storage capacity equals 1,169 KAF.

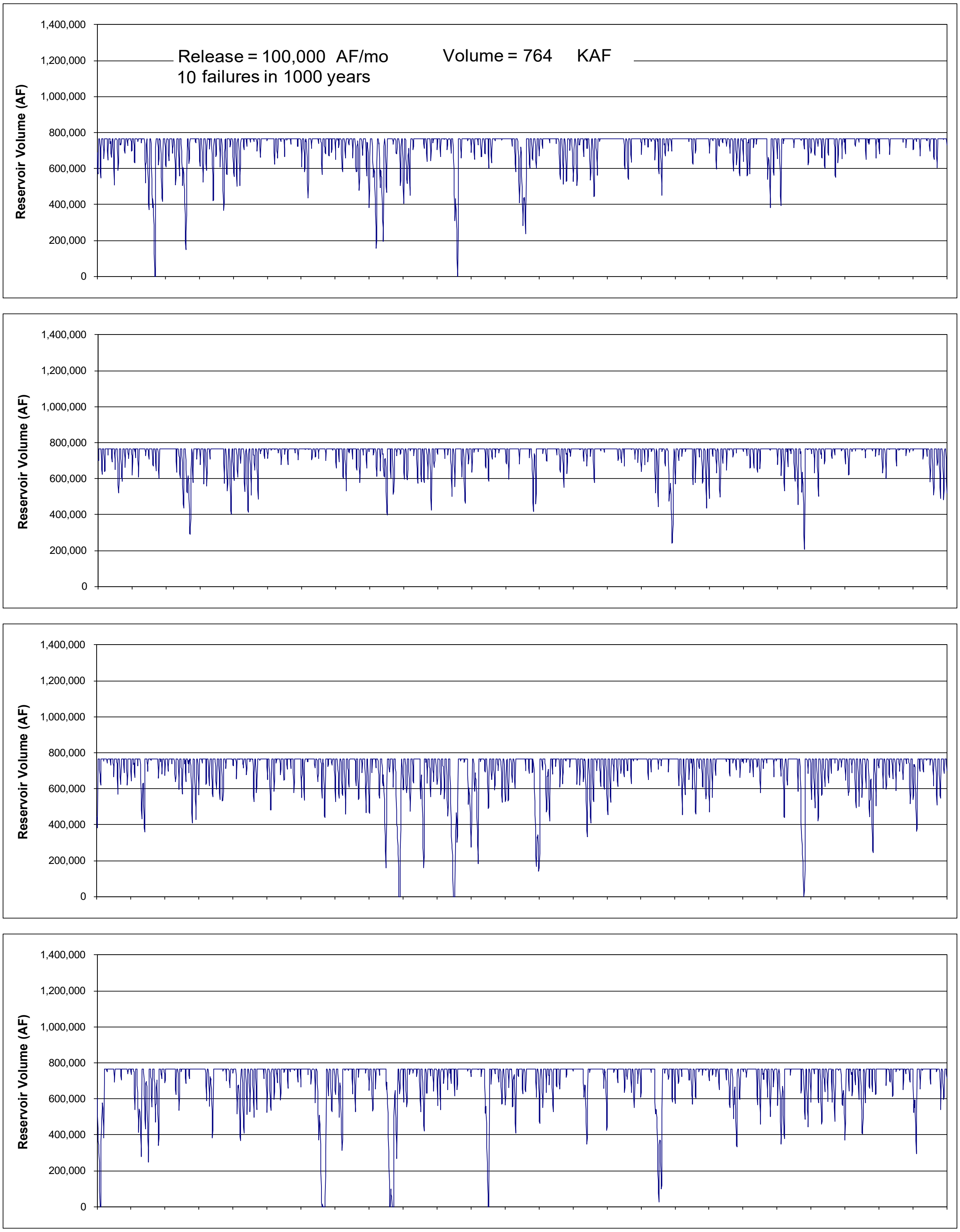

Figure A-44. Storage trace from a monthly 1,000-year simulation, finding storage capacity providing 10 failures in 1,000 years (99% reliability) for a demand equal to 100 KAF/month. Required storage capacity equals 764 KAF.

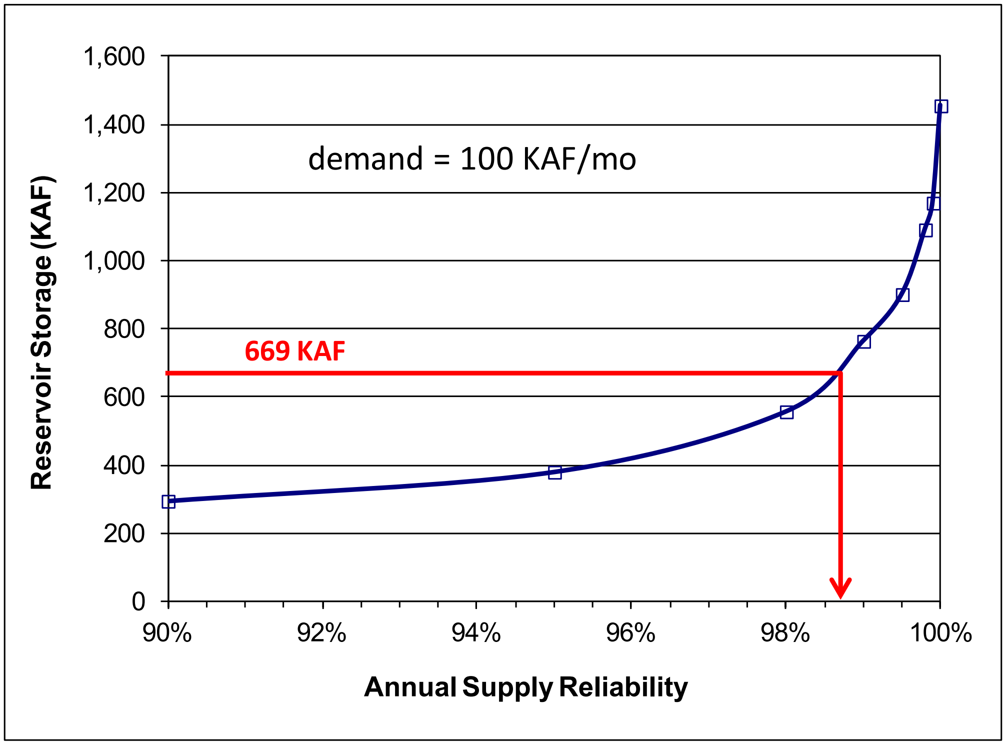

Figure A-45. Annual reliability versus reservoir storage for a demand of 100 KAF/month.

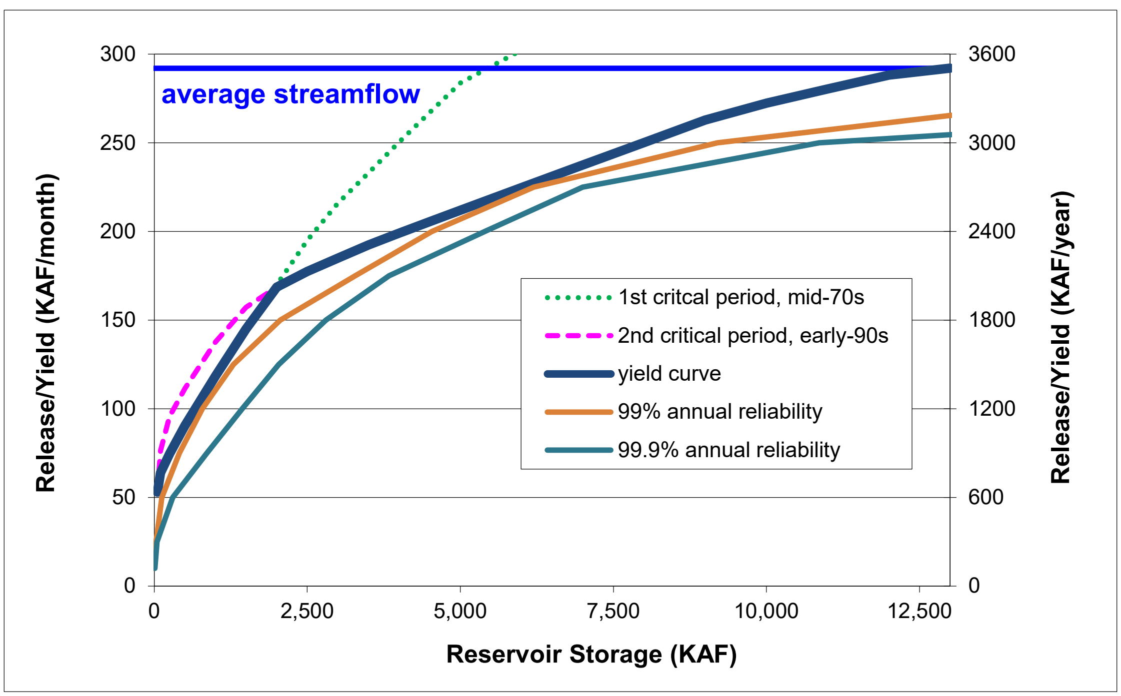

Figure A-46. Storage/yield relationship including 99% and 99.9% annual reliability.

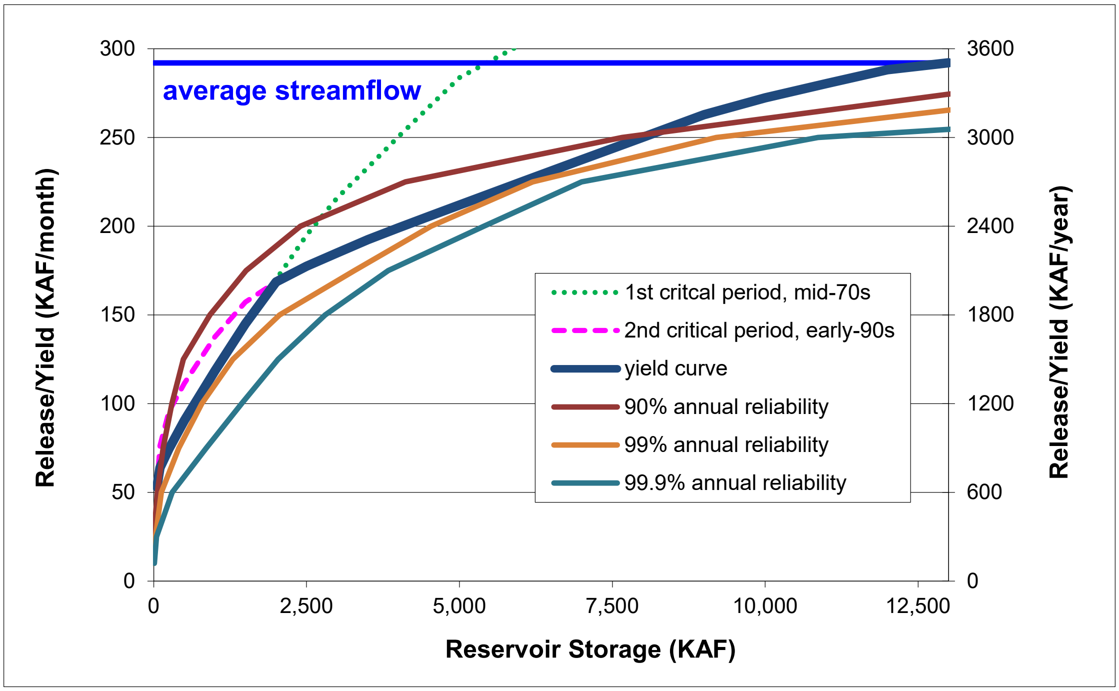

Figure A-47. Storage/yield relationship including 90%, 99% and 99.9% annual reliability.

g. Firm Yield or Storage Requirement for N-year reliability.

(1) A water demand or storage volume considered across N years (e.g., N = 50) has more opportunities for failure than a single year, and so will provide a lower reliability than the annual reliabilities computed in paragraph A-10.e.(1)(a). Like the annual reliability method (paragraph A-10.e.(1)(a)), the N-year reliability method (see paragraph A-10.e.(1)(b)) is demonstrated using the same 41-year streamflow series used in paragraph A-4 to demonstrate the simple yield techniques. Considering a project life of 50 years, the AR(1) model described in paragraph A-10.f.(1) (for log flow with skew using Pearson Type III error) was used to generate 500 different 50-year records of annual flow volumes. For each annual flow volume, one of five monthly flow patterns was randomly chosen to disaggregate the annual volume to monthly flows. Each of the 50-year long monthly records was used to compute firm yield for a given storage volume, or storage requirement for a given firm yield. To avoid the situation that a drought at the end of the record was incomplete, the 50-year record was repeated. It is expected that the storage requirement to supply demand without fail over a 50-year period would be larger than that for the initial 41-year period, as there is more opportunity for drought in a longer record. Similarly, the firm yield is expected to be smaller for a given storage volume.

(2) In paragraph A-4, Figure A-6 showed that the storage requirement for a demand of 100 KAF/month is 669 KAF for the 41-year record, resulting from the mid-1970s critical period. When computing the storage requirement for each of the 500 synthetic 50-year records, the average is 579 KAF, which is surprisingly less than the 669 KAF, implying that the critical drought in the 41-year actual record was more severe than expected for that record length. A histogram of values is shown in Figure A-48. The diamonds represent histogram vertical bars, and the red line is the 669 KAF from the actual 41-year period. The range of storage estimates is

extremely wide, and the distribution is very positively skewed (long upper tail). Figure A-48 also shows the 500 estimates of required storage ordered as a CDF (cumulative distribution function), with 69% of the estimates less than the original deterministic storage requirement of 669 KAF from the 41-year record. The CDF can offer estimates of reliability across the 50-year project life, with the example of 90% reliability in meeting the 100 KAF/month demand without fail for 50 years requiring 943 KAF, as shown by the green dotted line in Figure A-48. This required storage value is larger than that required for 99% annual reliability (764 KAF), as computed in Paragraph A-10.f., demonstrating that reliability across 50-years is a more stringent measure than annual reliability.

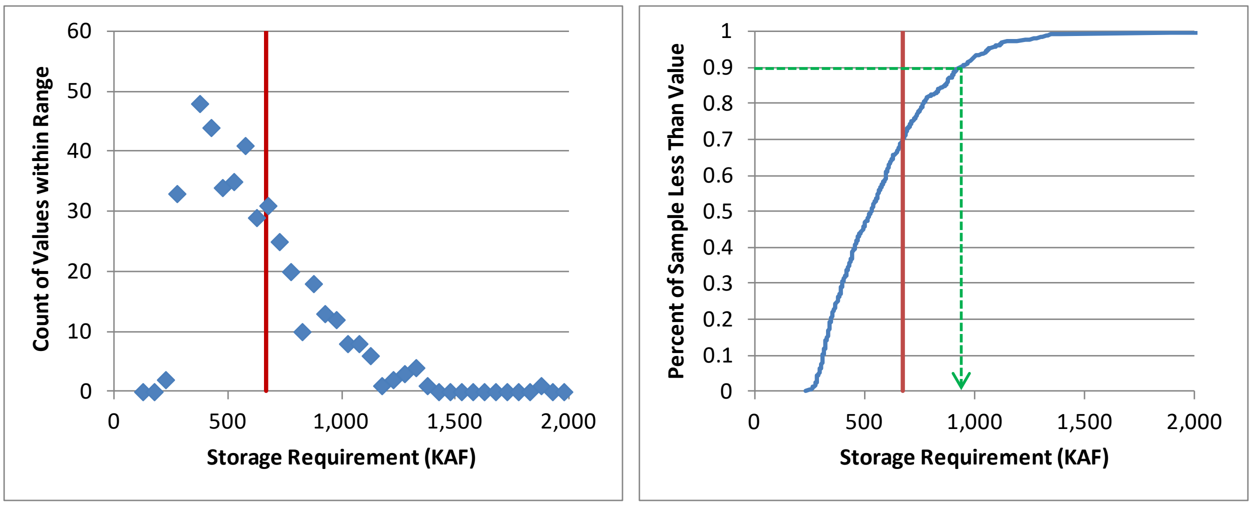

Figure A-48. 500 estimates of required storage for a demand that equals 100 KAF/month over 50 years, initial estimate (red) equals 669 KAF, 90% reliability from 943 KAF.

(3) From Figure A-7 in paragraph A-4.b., the original 41-year record provided a deterministic estimate of 4,068 KAF as the storage required for a demand of 200 KAF/month, resulting from the early 1990s critical period. From the 500 synthetic 50-year records, 500 estimates of storage required to provide 200 KAF/month were made and summarized in Figure A-49. The average of the estimates is 4,057 KAF, and 61% of the estimates were less than the 4,068 KAF from the 41-year time-series. The distribution is again very wide and quite positively skewed. From the CDF, 90% reliability in supplying a demand of 200 KAF/month over 50 years would require storage of 6,130 KAF, as shown in Figure A-49. This value is larger than that required for 99% annual reliability (4,537 KAF), as computed in paragraph A-10.f., again demonstrating that reliability across 50-years is a more stringent measure than annual reliability.

(4) A similar analysis was performed to find the distribution of firm yield estimates for a given storage volume, rather than the storage volume needed for a given firm yield. Figure A-50 shows the results of the 500 synthetic 50-year records and their estimates of firm yield for a <u>storage capacity of 1,000 KAF</u>. The firm yield for 1,000 KAF was 118.4 KAF/month for the original 41-year record, resulting from the late 1970s critical period. Of the 500 estimates of firm yield across 50 years, the average was 127 KAF/month, with 36% of the estimates less than 118.4 KAF. It is again surprising that the average firm yield was higher for the longer 50-year record length, implying that the critical drought in the 41-year actual record was more severe

than expected for that record length. Looking at the histogram in Figure A-50, the distribution is nearly symmetrical, as opposed to the positively skewed distributions for storage requirement in Figure A-48 and A-49. However, the kurtosis is quite negative (short, thick tails) due to the absence of extreme estimates. It is possible that the lack of extreme estimates is related to the relatively small storage required for firm yield of only one-third of the average annual inflow, an idea that can be tested by evaluating a larger storage, as is done below. The CDF in the second plot of Figure A-50 can offer estimates of reliability across the 50-year project life, with 90% reliability (only 10% of the values having lower firm yield) achieved in providing 101 KAF/month. This yield value is smaller than the 112 KAF/month firm yield having 99% annual reliability, as computed in paragraph A-10.f., again demonstrating that reliability across 50 years is a more stringent measure than annual reliability.

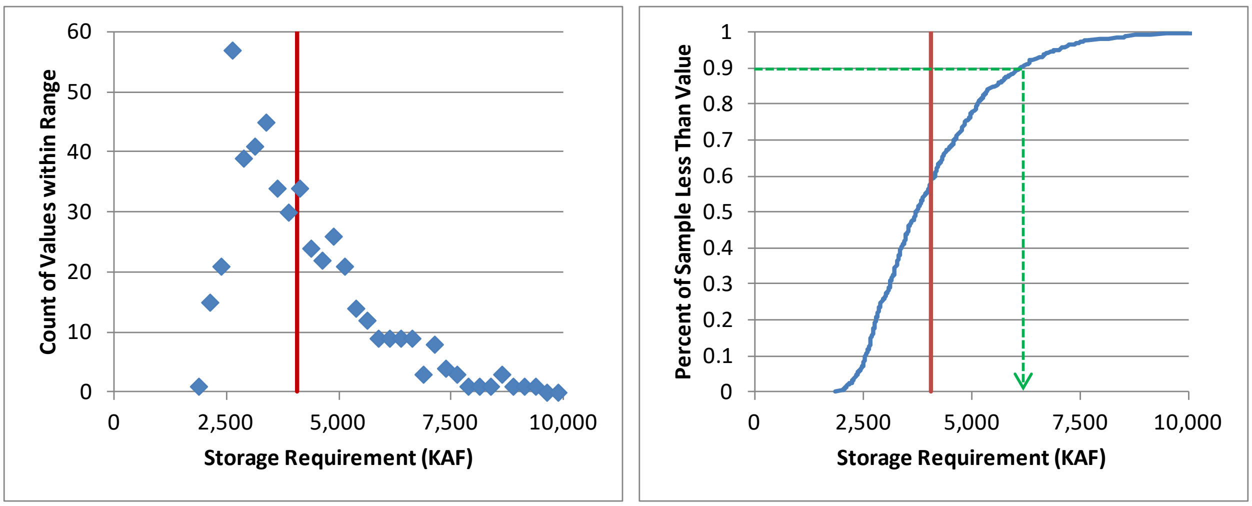

Figure A-49. 500 estimates of required storage for a demand that equals 200 KAF/month over 50 years, initial estimate (red) equals 4,068 KAF, 90% reliability from 6,130 KAF.

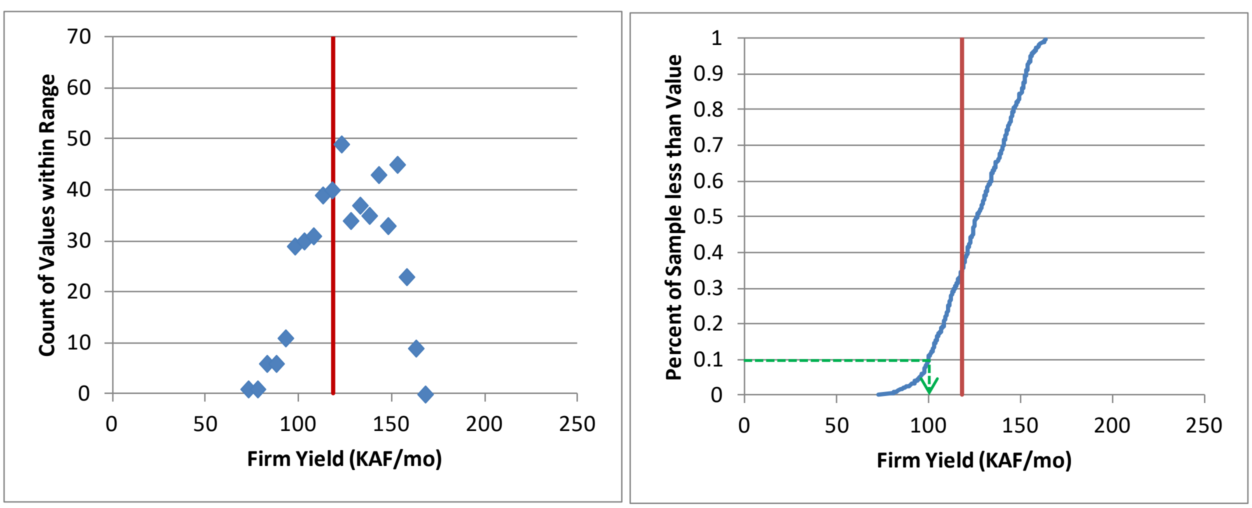

Figure A-50. 500 estimates of firm yield over 50 years for a storage capacity equal to 1,000 KAF, initial estimate (red) equals 118.4 KAF/month, average equals 126 KAF, firm yield with 90% reliability over 50 years equals 100 KAF/month.

(5) Figure A-51 shows estimates of firm yield for a larger storage capacity of 6,000 KAF. The firm yield for 6,000 KAF was 225 KAF/month in the original 41-year record, based on the 1986 through 1994 critical period. From the 500 estimates, the average was 232 KAF/month, and 38% of the estimates were less than the 225 KAF/month from the deterministic analysis of the 41-year actual record. This result, like the result for the 1,000 KAF firm yield, suggests the critical period may be more extreme than expected in a 41-year record. The distribution is again nearly symmetrical, but for this larger storage volume the kurtosis is much closer to zero, due to more extreme estimates (longer tails). The CDF in the second plot of Figure A-51 can offer estimates of reliability across the 50-year project life, with 90% reliability (only 10% of the values having lower firm yield) in providing 199 KAF/month shown in Figure A-51. This yield value is smaller than the 222 KAF/month firm yield having 99% annual reliability, as computed in paragraph A-10.f., again demonstrating that reliability across 50-years is a more stringent measure than annual reliability.

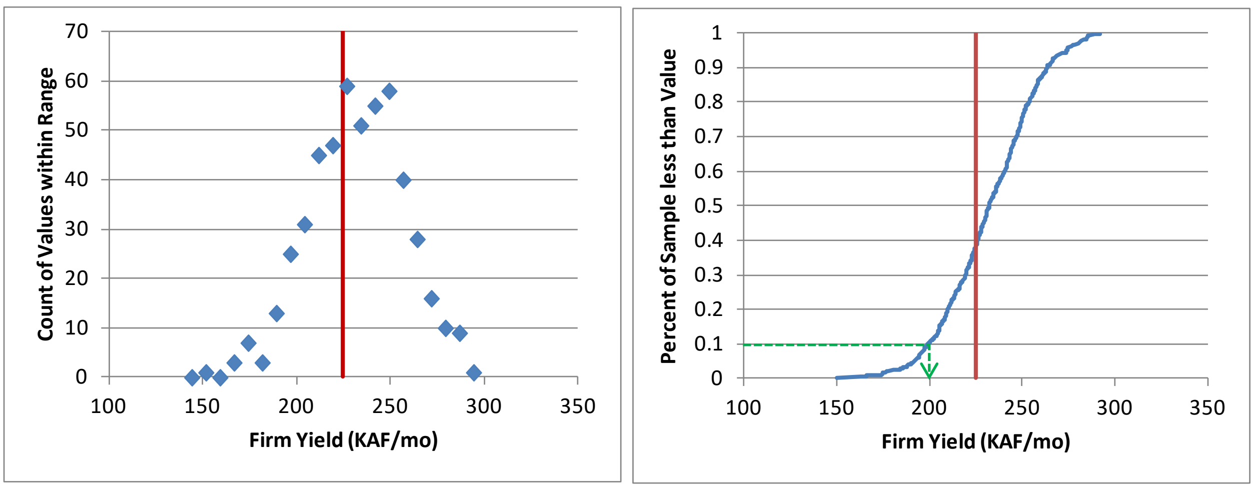

Figure A-51. 500 estimates of firm yield over 50 years for a storage capacity equal to 6,000 KAF, initial estimate (red) equals 225 KAF/month, average equals 232 KAF, firm yield with 90% reliability over 50 years equals 199 KAF/month.

(6) Finally, to determine how the presence or absence of extreme firm yield estimates is influenced by the storage volume, and how close the firm yield estimates are to the average annual flow, a distribution was also generated for the firm yield associated with a storage capacity of 10,000 KAF, which was 272.2 KAF/month in the actual data set. Figure A-52 shows the results of 500 synthetic 50-year time series, providing an average firm yield of 263 KAF/month, with 65% of the estimates below the value from the actual data set. While the skew has become slightly negative (longer lower tail), the kurtosis has become slightly positive because the analysis had more extreme estimates (as predicted above for yield close to average streamflow). In this case, the outcome of a lower average yield and 65% of the distribution being less than the deterministic 41-year yield estimate is as expected, with the longer 50-year period having smaller firm yield. The CDF in the second plot of Figure A-52 can offer estimates of reliability across the 50-year project life, with 90% reliability (only 10% of the values having lower firm yield) in providing 233 KAF/month as shown in Figure A-52. This value is smaller than the 255 KAF/month firm yield having 99% annual reliability, as computed in paragraph A-

10.f., again demonstrating that reliability across 50-years is a more stringent measure than annual reliability.

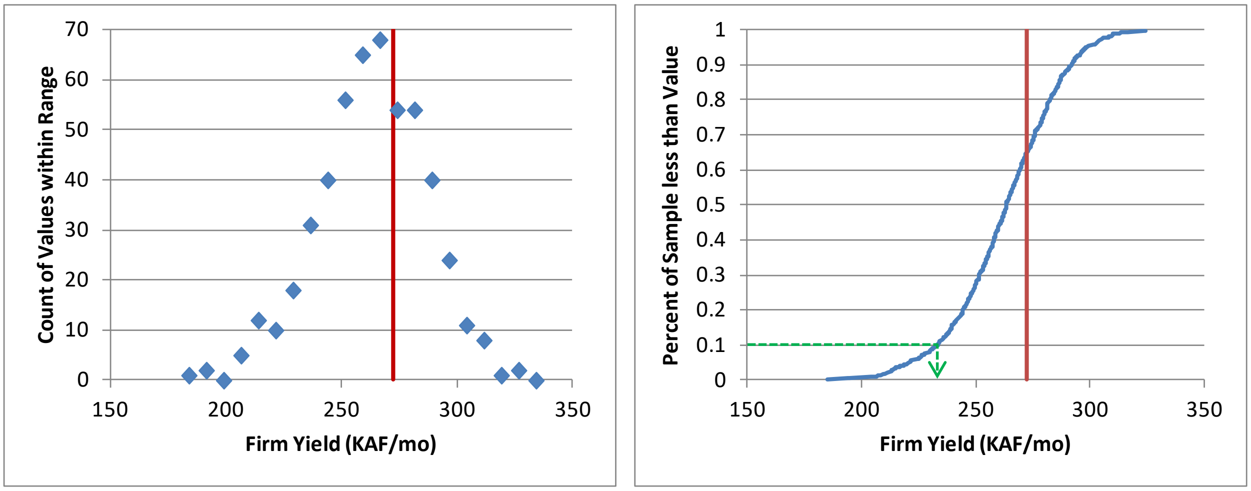

Figure A-52. 500 estimates of firm yield over 50 years for a storage volume equal to 10,000 KAF, initial estimate (red) equals 272.2 KAF/month, average equals 263 KAF, firm yield with 90% reliability over 50 years equal to 233 KAF/month.

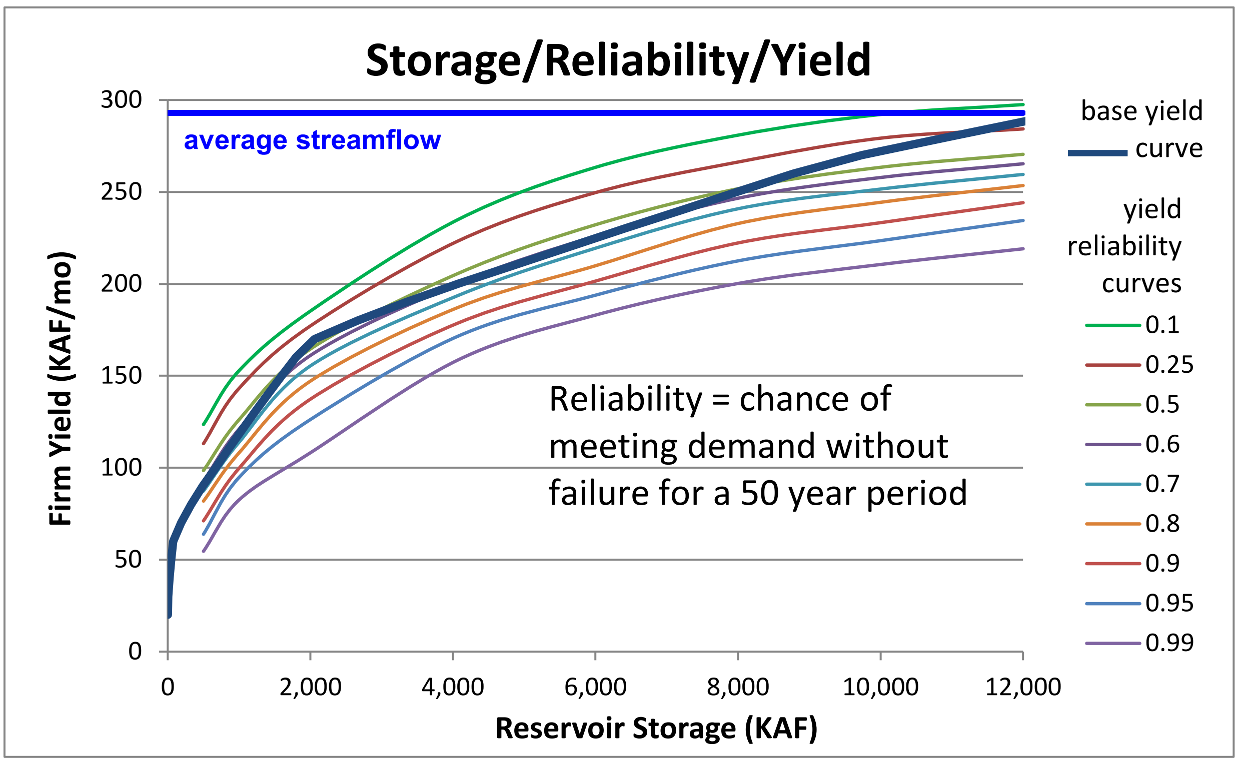

Figure A-53. Storage/yield relationship showing curves with various 50-year reliabilities.

(7) This second stochastic analysis method has focused on estimating reliability across an N-year project life, rather than annual reliability. Figure A-53 displays the storage/yield relationship for the initial 41-year record, and lines for 50-year reliabilities between 1% and

99%. Note the 99% 50-year reliability curve is much lower than the 99% annual reliability curve in Figure A-46. If each year were independent of the previous year, a binomial distribution could be used to compute the annual reliability associated with a 50-year reliability of 99%. Independence would tell us that a 50-year-reliability equals annual-reliability to the 50th power (e.g., 99% annual reliability provides 0.9950 = 60.5% reliability over 50 independent years). Similarly, annual-reliability equals 50-year reliability to the 1/N power (e.g., for 90% reliability over 50 years, annual reliability is equal to 0.91/50 = 99.8%). However, in the case of serially correlated annual volumes, these binomial relationships do not apply, which is the reason for the more detailed analysis shown here. For serial correlation below 15%, the binomial relationships may be adequate.

h. Multiple yield requirements with different reliabilities.

(1) USACE, 1967 and USACE, 1975 both describe a process to determine the storage requirement for one supply with a higher reliability and another supply with a lower reliability. The assumption is that the reservoir would stop supplying the lower reliability water need at some point to be able to supply the higher priority need longer.

(2) As an example, one water need of X cfs has a 1% allowable failure rate and another water need of Y cfs has a 10% allowable failure rate. Need-Y allows failure more often, and so when supply is short, the Y cfs will be cut off before the X cfs. To determine the required volume to supply both X and Y at their required reliabilities, the first step is to create a storage/yield relationship with a 1% failure rate, and another version of the relationship for a 10% failure rate, with the latter obviously showing less storage required for a given yield. Then the entire storage need for X+Y cfs is looked up on each curve. SXY.1% is the storage volume needed to supply the entire need X+Y cfs at 1% chance of failure, and SXY.10% is the smaller volume needed to supply the entire need X+Y cfs at 10% chance of failure. The required storage volume will then be at least SXY.10%, but an additional volume is required to supply only X cfs to the 1% failure rate. The portion of the (SXY.1% – SXY.10%) additional volume that's needed is the ratio X/(X+Y). Thus, the total volume is:

$$SXY.10\% + (SXY.1\% - SXY.10\%) * X/(X+Y) \qquad \text{(A-6)}$$

(3) An additional question is how to operate to achieve these failure rates, i.e., at what storage level is the Y cfs cut off while continuing to supply the X cfs. The cut-off volume is found by looking up the storage need for only X cfs on each storage/yield curve, to find values identified as SX.1% and SX.10%. The difference between these two volumes is the additional volume needed to increase the reliability of X cfs from 10% failure rate to the 1% failure rate. This difference is therefore the volume that must be reserved for only satisfying the X cfs, and so when storage level gets down to (SX.1% – SX.10%), delivery of the Y cfs is stopped.

(4) When determining the storage volume required by a particular user, it can be important to specify the reliability with which the supply must be met, the ability of the demand to be reduced in dry conditions, and, if the supply is actually an add-on to a more regular supply that might be inadequate in dry times, the frequency with which the supply might be needed. This latter type of supply will most likely only be called upon during dry times, and so in an

analysis of a critical period, it would be present the entire time, the same as other types of use. The sense of this outcome stems from the fact that an allocated storage volume will be drawn upon most heavily during the critical period, which is why we define safe or firm yield by analyzing critical periods. It is common for some volume not to be needed in wet times, and this does not make the volume less necessary.

i. Reliability Summary.

(1) Paragraph A-10 has discussed the issue of uncertainty in the firm yield estimate, and suggested consideration of reliability of meeting the historical firm yield as a way to quantify that uncertainty. Four methods were described to evaluate uncertainty/reliability, two based on frequency analysis of the historical record (non-sequential mass curve and synthetic balanced drought) and two using stochastic streamflow generation (annual and N-year reliability). These concepts are, presented for consideration and discussion. No recommendation is yet made for the appropriate level of reliability in a firm yield estimate, or for the best method for evaluation.

A-11. **Yield in Multi-Reservoir Systems**.

a. Analysis of the firm yield of a system of reservoirs can be very similar to that of a single reservoir, and uses the methods described in this document. However, different system configurations and levels of coordination might require different approaches, sometimes involving a sequence of yield analyses. In the following discussion, the term “system” is used to refer to multiple reservoirs, although the degree to which they operate together for common goals varies. Given a group of reservoirs operating on the same stream, or tributaries to a stream, the question of whether they are jointly owned with coordinated operation, or are separately owned and operated independently, has an impact on the yield they provide. (Note: Coordinated operation could also exist with separately owned reservoirs.) The assumption of coordinated operation, or the lack thereof, also affects how the yield of each reservoir would be determined. This section contains discussion of reservoirs in parallel and reservoirs in series, and for each case whether the reservoirs are jointly operated and meeting common goals, or not.

b. Parallel System.

(1) Separately operated parallel system.

(a) When reservoirs in parallel are separately owned and operated independently, the firm yield at each reservoir can be computed separately, with each reservoir responsible for meeting its own demand. Figure A-54 shows two reservoirs in parallel. For users taking water directly from the reservoir pools or from immediately below the reservoirs, these per-reservoir yields are the values of interest. Each reservoir is evaluated with iterative simulation to determine the maximum consistent release at that reservoir, either for the actual reservoir with its existing Conservation Pool (seasonal or constant), or for other storage capacities to determine a storage/yield curve for the site. To consider a single user in the Conservation Pool, yield provided by a range of storage account sizes within the reservoir's Conservation Pool can also be evaluated.

(b) For the example in Figure A-54, reservoir data is shown in Table A-1.

Table A-1. Reservoir Data.

	East Reservoir	West Reservoir	
		Winter	Summer
Storage capacity	1,100 KAF	150 KAF	250 KAF
Average Annual Inflow	1,480 KAF	1,170 KAF	
Storable percentage	75%	13%	21%
Average inflow	2,050 cfs	1,600 cfs	

(c) Note that East Reservoir can store 75% of its average annual inflow, while West Reservoir can store only thirteen to 21%. These ratios suggest a longer critical period for East Reservoir and a shorter critical period for West Reservoir. Since West Reservoir is less able to store water in preparation for a dry period, it is easily stressed by a single very dry year.

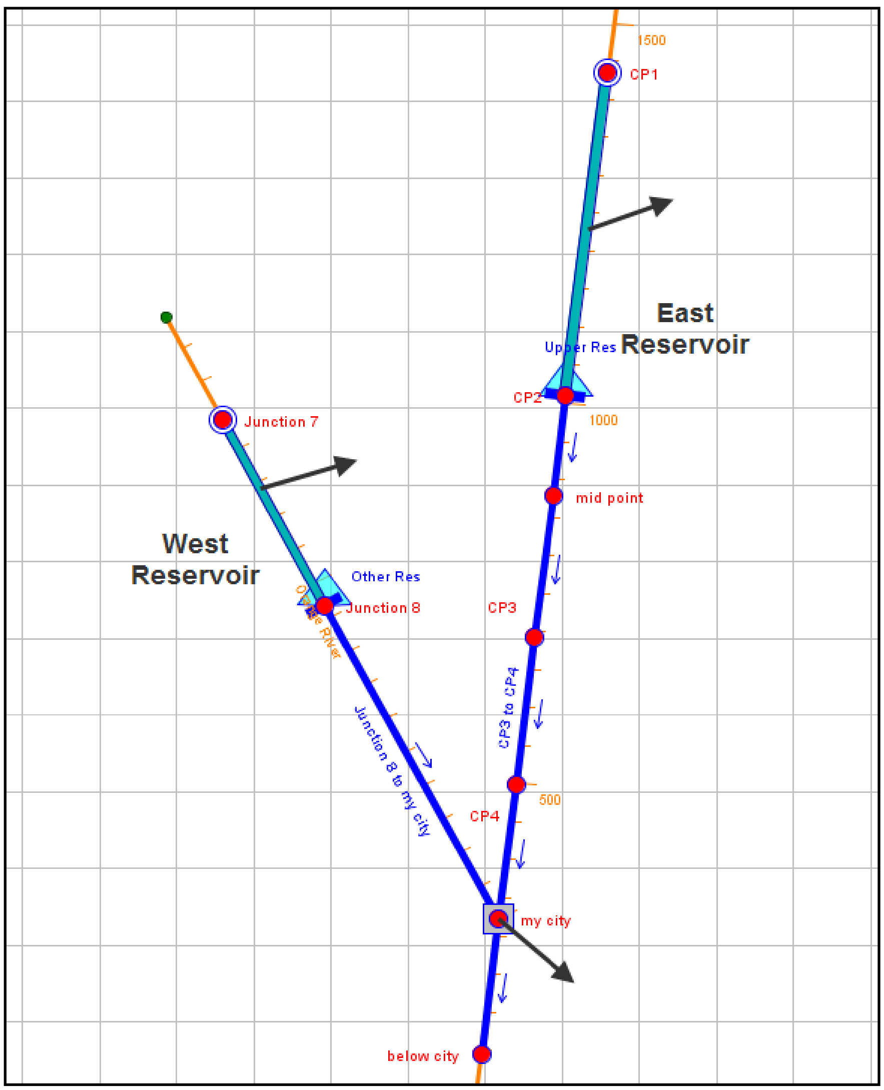

Figure A-54. Schematic of two reservoirs in parallel.

(d) For constant demands, iterative simulation determined that the firm yield of East Reservoir is 1,479 cfs, and the firm yield of West Reservoir is 673 cfs. The time-series of storage and outflow is shown in Figure A-55 as solid red lines. (Reservoir diversions are included in "outflow.") Surprisingly, East Reservoir has two very similar multi-year critical periods, the first drafting storage by November 1957 and the second drafting storage by January 1989. The 1957 period is slightly more critical, identified because the reservoir empties completely, and so is the period that defines the firm yield. At West Reservoir, which has a much smaller storage volume compared to its inflow and a more extreme flood pool evacuation, the critical period is a single year in 1986.

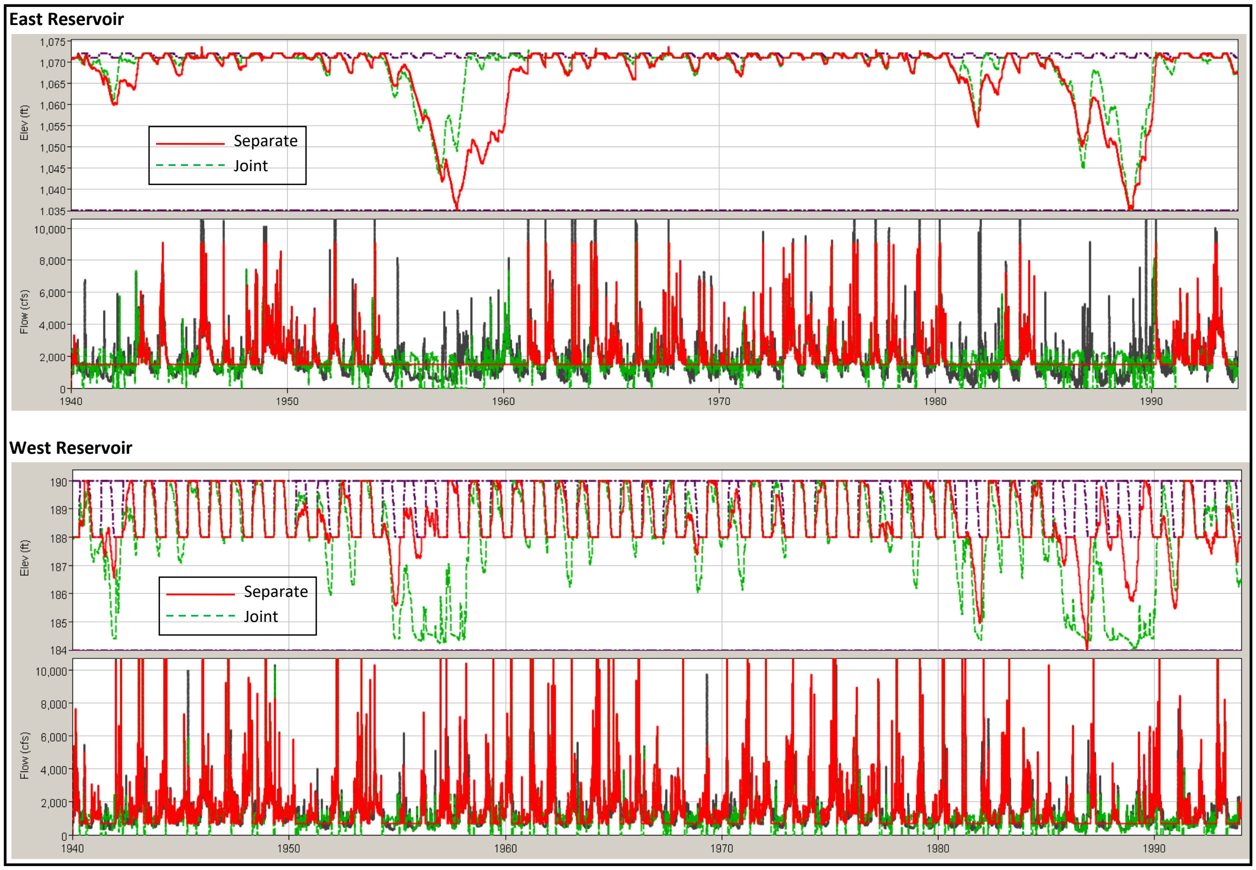

Figure A-55. Time-series plots of reservoir storage and inflow/outflow for two reservoirs in parallel, operated separately (red, total firm yield equals 2,152 cfs) and as a joint reservoir system (green, firm yield equals 2,454 cfs).

(e) One way to summarize these results is to specify that East Reservoir provides a yield of 1.3 cfs/KAF, and West Reservoir provides a yield of 3.3 cfs/average-KAF. West Reservoir is more difficult to summarize with this metric for the same reason it is difficult to construct a storage/yield curve for a reservoir with a variable storage capacity (Guide Curve). The computed yield value respects the changing capacity, but there is not a single capacity value to plot in a storage/yield curve or a cfs-per-KAF value. (The estimate of 3.3 cfs/average-KAF is based on the annual average storage volume of 200 KAF.)

(f) Note: This simulation did not include return flow from diversions. If flow from diversions does physically return to the reservoir, that flow could perhaps be included for an accurate simulation. However, physical return does not imply credit given to a water user for that return, and so analysis of storage account yield, discussed later, might show physical return without credit.

(2) Jointly operated parallel system.

(a) When reservoirs in parallel have coordinated operation, those reservoirs have the opportunity to cooperate in meeting a common goal such as a downstream flow diversion. For users below the confluence, who can be served by either reservoir, the total firm yield of the system might be greater than the sum of the single-reservoir firm yields. There can be several reasons for this increase. First, additional local inflows below the reservoirs but above the diversion site would contribute to yield. But more importantly, the reservoirs working in concert can operate more effectively to take advantage of inflow variations between the reservoirs and differing storage abilities, for example providing more water from a reservoir that refills more easily.

(b) Determining the yield of a parallel system of reservoirs meeting a shared downstream goal uses a single application of the iterative simulation approach. With a simulation tool that can truly operate reservoirs as a system (perhaps by maintaining some storage balance), the computation iteratively maximizes the downstream demand. In the example shown in Figure A-54, as stated above, the firm yield of East Reservoir alone is 1,479 cfs, and the firm yield of West Reservoir alone is 673 cfs, totaling 2,152 cfs for both reservoirs. However, at a point downstream that can be served by either reservoir, the total firm yield is 2,454 cfs, with no additional inflow below the reservoirs. The joint operation provided an additional 302 cfs in firm yield – an increase of 14%. (This firm yield can be summarized as 1.9 cfs/average-KAF.) Figure A-55, shows separate operation as red lines, and shows the joint operation of the reservoirs as dotted green lines. The system storage balance has been defined to draft a greater percent-of-pool from West Reservoir than East Reservoir, to take advantage of West Reservoir's higher inflow/storage ratio and allow for the winter flood pool not permitting winter storage. In the separate operation case (Figure A-55, solid red lines), East Reservoir has two very similar critical periods while West Reservoir has a much shorter critical period at a different time. However, when the reservoirs are operated jointly (Figure A-55, dotted green lines), they share East Reservoir's later critical period. East Reservoir easily provides water during West Reservoir's single dry year, and West Reservoir uses some otherwise-spilled water to increase release during both of East Reservoir's critical periods.

(c) It is possible for the reservoirs to operate jointly for a purpose such as a downstream flow augmentation or hydropower but serve the water supply need separately. In this case, there is some required storage balance between the reservoirs, but with separate diversions for supply from each pool. This situation will be discussed in paragraph A-12.

c. Series System.

(1) For reservoirs in series (tandem), whether jointly owned or separately owned and operated, firm yield cannot be computed for one reservoir without some assumptions made about the operation of reservoirs upstream. Figure A-56 depicts two reservoirs in series. The water rights system applicable to the reservoirs may affect interactions between reservoirs on the stream. For a reservoir in the Western States, following the "first in time, first in right" Prior Appropriation doctrine, the reservoir inflow may belong to the reservoir at a given time (and so be available to develop firm yield), or not, which is determined by the date of the reservoir's storage right and whether it is in priority. For the observed period of record, the ownership of the inflow (and so whether it is available) at each time-step can be determined and used in the yield analysis. However, if alternate operation of the reservoir would affect the downstream users and therefore the call on the river (and so the water rights in priority), the portion of available inflow may need to be determined within the reservoir analysis, which is a much more difficult task.

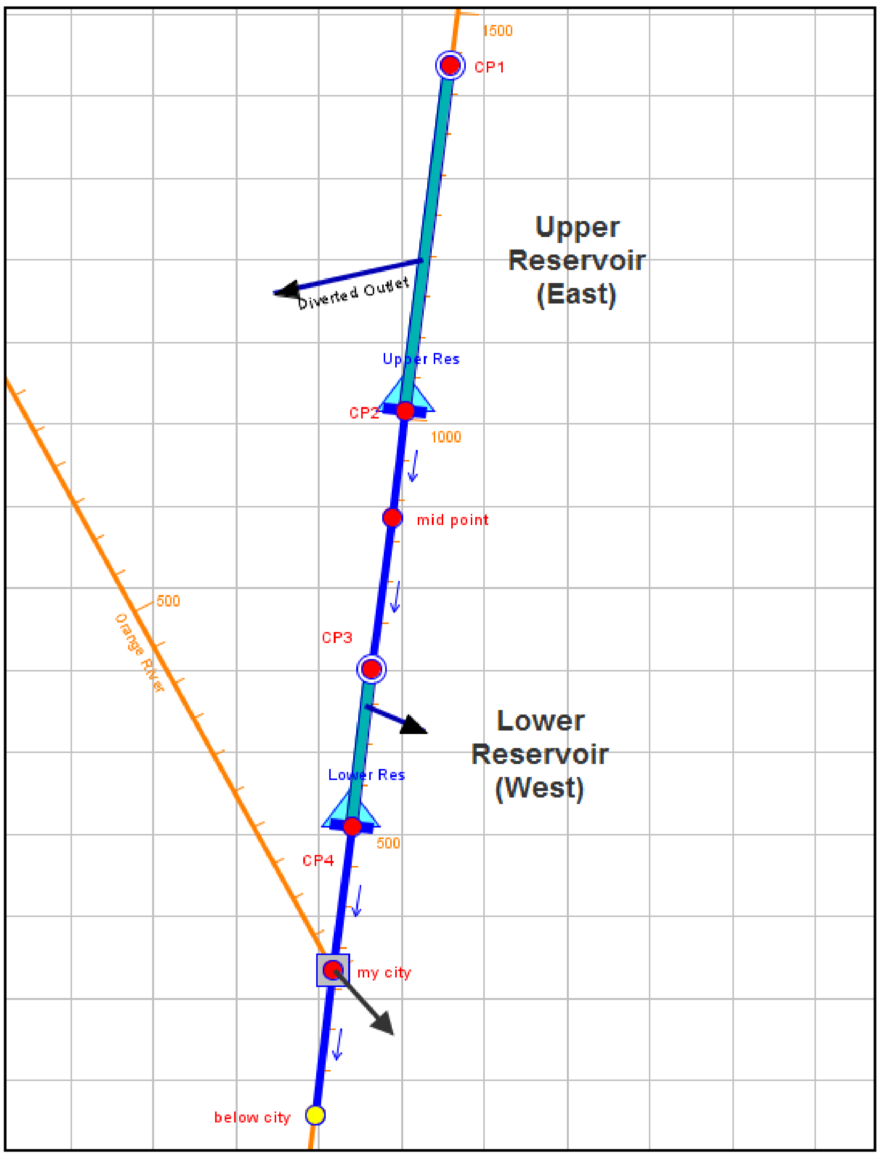

Figure A-56. Schematic of two reservoirs in series.

(2) For a series system of nonfederal reservoirs in the Eastern U.S. following the Riparian doctrine, water users on the river (including reservoirs) share the available supply equitably with other users. An upstream reservoir has the ability to detain and divert water for reasonable consumptive uses, making it unavailable downstream, but may be obligated to pass some of that water through to downstream users. For jointly-owned reservoirs operating as a system, the sharing of water might be explicit and coordinated. Upper and Lower Reservoirs in Figure A-56 form a system that can operate together toward water-use objectives. To aid comparison, Upper and Lower Reservoirs are actually the same two reservoirs that were shown in parallel as East and West Reservoirs, respectively, in Figure A-54, with the same capacities and inflows shown in Table A-1. Operating the two reservoirs jointly can supply yield as a system, and, as with reservoirs in parallel, the system firm yield can be computed by iterative simulation with a model that captures the coordinated operation. Evaluating yield of individually owned and operated reservoirs in a series presents more complexity and will be discussed after joint operation.

(3) Jointly operated series system.

(a) For jointly operated reservoirs in series, a sequence of firm yield computations is needed. The first step is to compute a firm yield available as one proceeds from upstream to downstream in the system. Users at the upstream reservoir have a smaller firm yield available to them than users at the downstream reservoir, because the downstream reservoir has the benefit of more inflow and more storage space due to its position in the series system of both reservoirs. In Figure A-56, Upper Reservoir provides a maximum firm yield of 1,479 cfs (summarizing to 1.3 cfs/KAF). (Note: this firm yield is the same as that of the identical East Reservoir in the parallel system example.) Maximizing firm yield at Lower Reservoir, with the two reservoirs acting in concert, provides 2,454 cfs (summarizing to 1.9 cfs/average-KAF). (Note: this yield is also the same as the total yield for the two identical reservoirs acting as a parallel system.) Figure A-57 shows the reservoir time-series for maximum firm yield at Upper Reservoir (solid red lines) and maximum total firm yield at Lower Reservoir (dashed green lines). The green dashed "Max Total" reservoir elevation series are identical to the "joint" parallel reservoirs case shown in Figure A-55. The inflow/outflow at Upper Reservoir is also the same as the parallel case, but the inflow/outflow at Lower Reservoir is different, because when positioned in series, that reservoir now receives the outflow from Upper Reservoir. The solid red "Max Upper" elevation series at Upper Reservoir is also identical to the "separate" parallel reservoirs case in Figure A-54, and if a diversion of 673 cfs were added at Lower Reservoir, the series at Lower Reservoir would be identical as well.

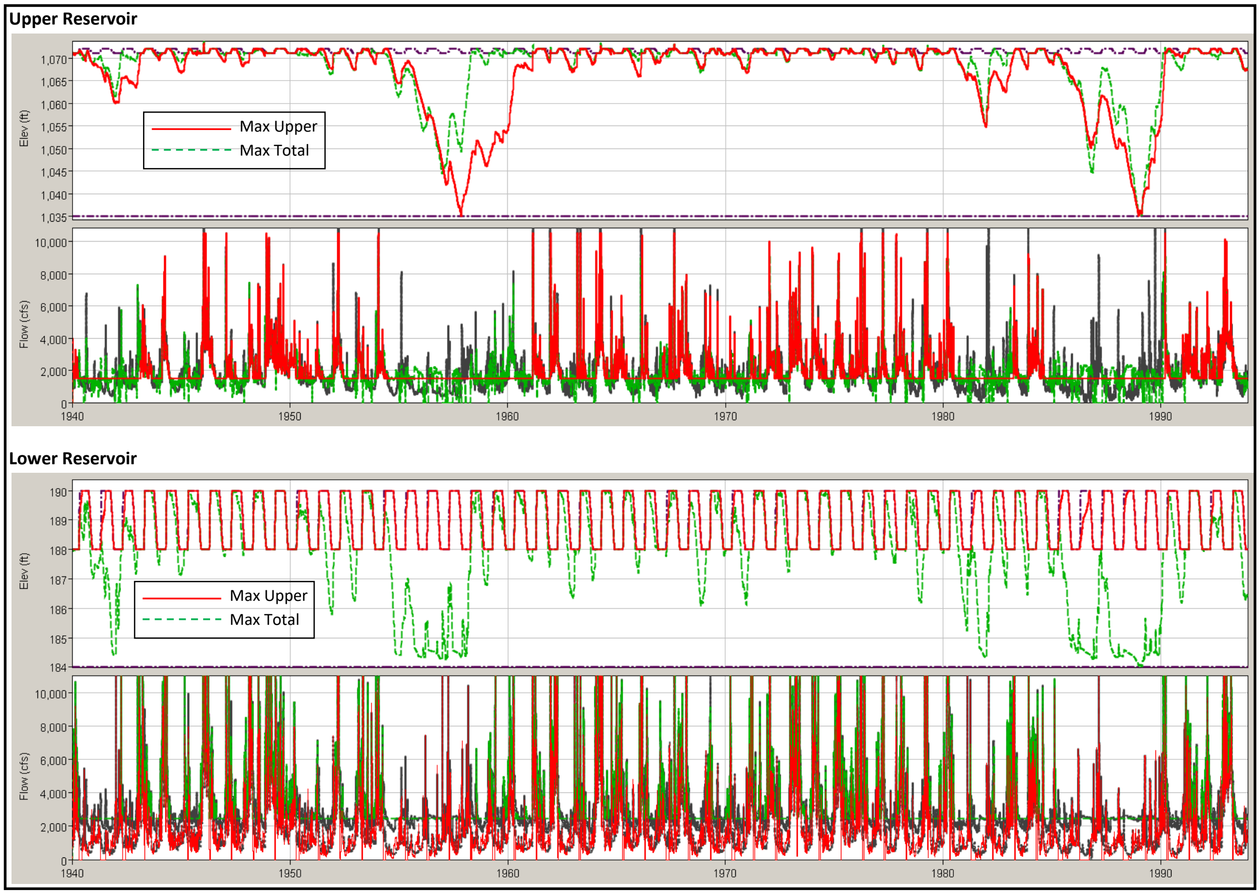

Figure A-57. Time-series plots of reservoir storage and inflow/outflow for two reservoirs in series, maximizing yield at Upper (red, firm yield equals 1,479 cfs) and then maximizing system yield at Lower (green, firm yield equals 2,454 cfs).

(b) Analysis thus far shows that users diverting from Upper Reservoir can get a maximum yield of 1,479 cfs. Users at Lower Reservoir could get a maximum of 2,454 cfs if there were no diversions from Upper Reservoir and the reservoirs followed coordinated operation (maintaining a defined storage balance that drafts Lower Reservoir more heavily than Upper Reservoir). The distribution of firm yield between the two reservoirs should perhaps be guided by the location of actual users and from which reservoir the uses would need to divert. If the choice were to remove 800 cfs at Upper Reservoir, with the system balance in place, iterative simulation shows that 1,594 cfs could be diverted at Lower Reservoir. Figure A-58 shows the resulting reservoir time-series. (Because of the system balance operation that drafts Lower Reservoir more heavily, it looks similar to the "Max Total" solid green lines in Figure A-57, though somewhat toward the red lines that maximize the diversion at Upper Reservoir.) The total of 800 cfs plus 1,594 cfs equals 2,394 cfs is less than the single diversion of 2,454 cfs at Lower Reservoir because this combination of diversion at both reservoirs does not allow the most efficient system operation. Although it is not always the case for a jointly operated series system, for this system of two reservoirs it is most efficient to divert water only from the bottom of the system, i.e., from Lower Reservoir. By evaluating a range of diversions from both reservoirs, setting the diversion at Upper Reservoir and maximizing diversions from Lower Reservoir, Table A-2 and Figure A-59 are produced. In Figure A-59, Upper Reservoir diversion is on the horizontal axis, Lower Reservoir diversion is on the vertical, with a solid red line, and the total diversion is on the vertical as a dashed blue line. Clearly, more diversion in the higher part of the system allows less diversion in the lower part of the system, and in this case, the largest total diversion (firm yield) comes from diverting only at the lowest point in the system.

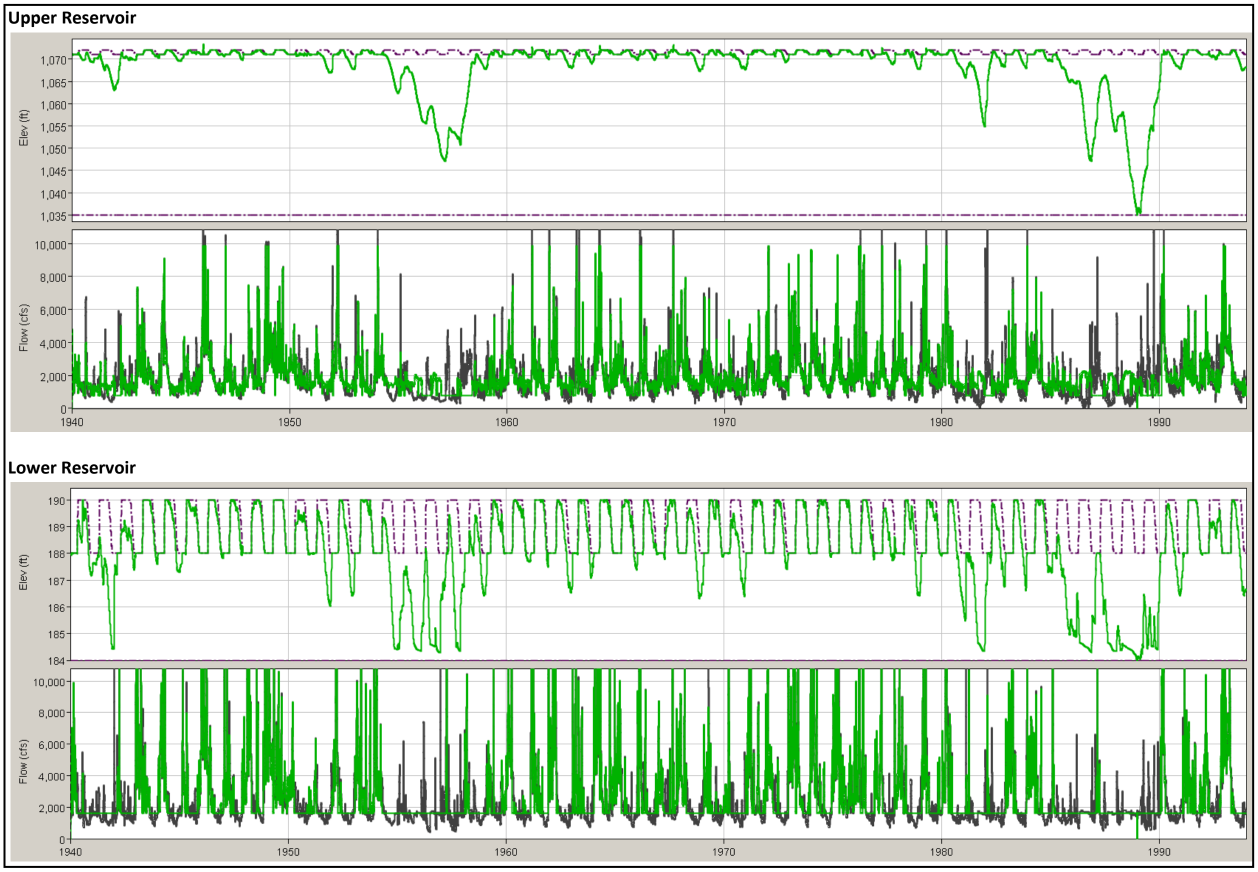

Figure A-58. Time-series plots of reservoir storage and inflow/outflow for two reservoirs in series, diverting 800 cfs from Upper Reservoir and 1,594 cfs from Lower Reservoir.

Table A-2. Maximized diversion from Upper and Lower Reservoirs for jointly operated reservoirs in series.

Upper Reservoir Diversion (cfs)	Lower Reservoir Diversion (cfs)	Total Diversion (cfs)
0	2,454	2,454
200	2,242	2,442
400	2,032	2,432
600	1,815	2,415
800	1,594	2,394
1,000	1,372	2,372
1,200	1,146	2,346
1,400	883	2,283
1,479	673	2,152

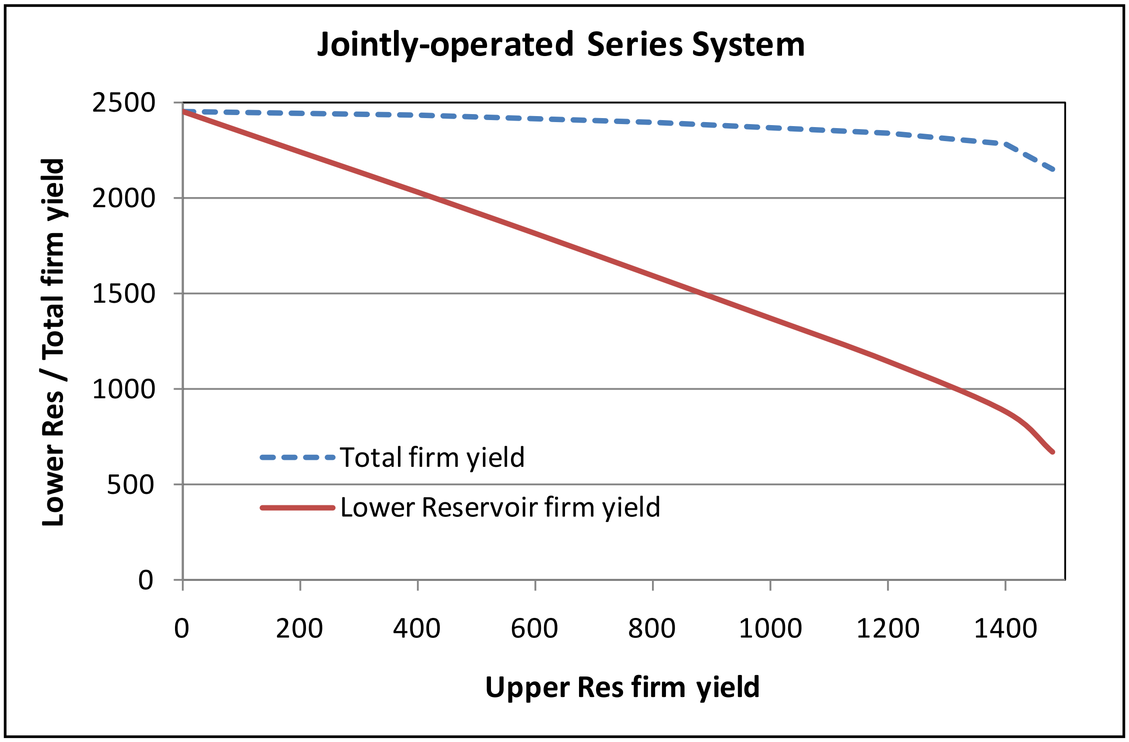

Figure A-59. Series system of two reservoirs, operated jointly.

(c) To summarize the computation of firm yield for a jointly operated system of reservoirs in series, the two-step analysis approach just described involves first evaluating firm yield for the case of diversion only at the lowest reservoir, proceeding from upstream reservoir to downstream reservoir, and then evaluating firm yield for increased diversions at upstream reservoirs and the resulting firm yield at downstream reservoirs. Although demonstrated with only two reservoirs to simplify the example, this approach can be used for three or more reservoirs. The combinations of diversion levels at upstream reservoirs and resulting maximum diversions at downstream reservoirs are more numerous with more reservoirs, thus requiring many more iterative yield simulations than the two-reservoir case.

(4) Separately operated series system.

(a) For a collection of reservoirs in series that is not jointly operated, the determination of firm yield of each reservoir is more difficult. Without a balanced operation to define reservoir cooperation, it is difficult to make assumptions about what flow would pass from the upstream to the downstream reservoir. The process of determining a firm yield for each reservoir is more involved than for the case of reservoirs in parallel (see paragraph A-11.b.), because the reservoirs cannot follow completely independent operation, as the downstream reservoir is affected by the releases from the upstream reservoir. The approach for separately owned reservoirs in series is a multi-step analysis process, although slightly different than the one for jointly operated reservoirs in series. The process will again be demonstrated with two reservoirs, although the same approach can be followed with three or more reservoirs.

(b) The first step in determining firm yield for separately operated reservoirs in series is to start with the assumption that the upstream reservoir completely develops its firm yield, which is then unavailable to the downstream reservoir. A firm yield for the upstream reservoir is computed first by maximizing its diversion. Subsequent iterative yield simulation includes the upstream reservoir diverting that firm yield and maximizes the diversion at the downstream reservoir. The downstream reservoir's resulting firm yield would then be a minimum value of what firm yield could be at that reservoir, which assumes no sharing of inflow from upstream. For the reservoirs evaluated here, shown in Figure A-56 in series, Upper Reservoir's firm yield is still 1,479 cfs, and the subsequent minimum firm yield at Lower Reservoir (with the reservoirs not coordinating their operation) is 673 cfs. (Note: These yields are the same as the separately operated parallel reservoir case and jointly operated series reservoir case in which Upper Reservoir diverts its maximum yield.) The total yield from both reservoirs is the sum of the yields, 2,152 cfs. Figure A-60 shows the reservoir time series for this case as solid red lines. (Note: Upper Reservoir releases no flow to Lower Reservoir during its multi-year critical periods, and so Lower Reservoir's firm yield from the 1986 critical period is based on inflow originating below Upper Reservoir—Lower Reservoir's "local" inflow.) This result is the reason the firm yield at Lower Reservoir is also the same as the case of parallel reservoirs.

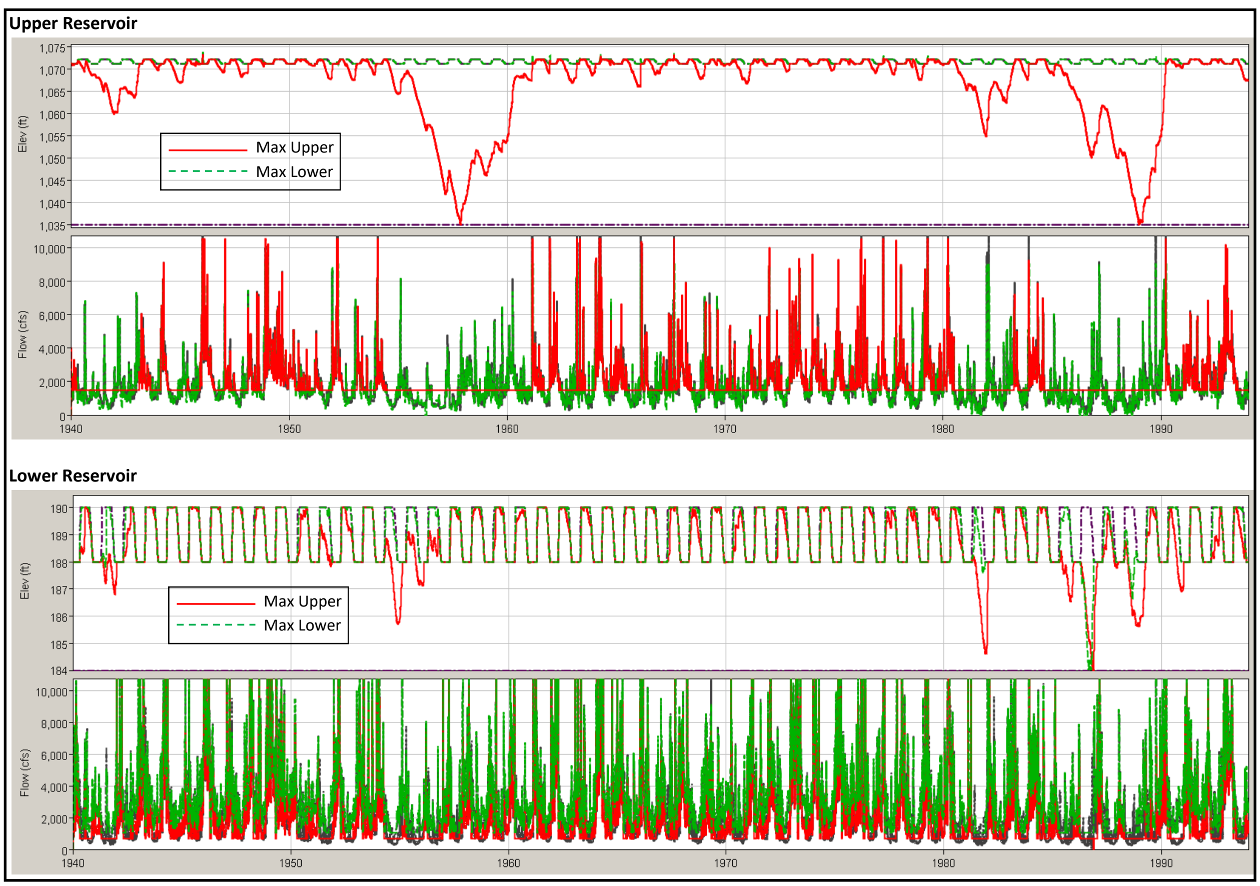

Figure A-60. Time-series plots of reservoir storage and inflow/outflow for two reservoirs in series, first maximizing yield at Upper Reservoir (red, yield equals 1,479 cfs at Upper Reservoir and 673 cfs at Lower Reservoir, providing a total of 2,152 cfs) and then maximizing yield at Lower Reservoir with no diversion from Upper Reservoir (green, yield equals 1,052 cfs).

(c) The next step in the yield analysis process uses the opposite assumption, determining firm yield at the downstream reservoir assuming the upstream reservoir is not present, or not diverting water, making the entire watershed's runoff available to the downstream reservoir. Computing firm yield in this way provides a maximum value of what firm yield could be at the downstream reservoir if it were alone in the watershed. For this system of reservoirs, with no diversion at Upper Reservoir, the firm yield at Lower Reservoir is 1,052 cfs. Figure A-60 shows this case as the dashed green lines. Note: The total diversion of 1,052 cfs is less than half that of maximizing diversion at Upper Reservoir, because Upper Reservoir's storage is not utilized at all in this case. Both cases (maximum diversion at Upper Reservoir and no diversion at Upper Reservoir) show total yield less than the 2,454 cfs available when the reservoirs are coordinated. In both cases, the critical period at Lower Reservoir is Spring to Fall of 1986.

(d) Neither of the assumptions – the upstream reservoir diverts all the water it can, or diverts nothing – is accurate, and a more reasonable assumption is somewhere in between these extremes. The actual yield assigned to the downstream reservoir would sensibly fall between minimum and maximum values representing these extreme assumptions. Therefore, the yield at Lower Reservoir is determined to be between 673 cfs and 1,052 cfs. Next, a trade-off curve can be developed, trying many different Upper/Lower reservoir yield allocations by setting the diversion from Upper Reservoir to values between zero and 1,479 cfs, and maximizing the diversion at Lower Reservoir for each. This process develops Table A-3 and Figure A-61.

Table A-3. Maximized diversion from Upper and Lower Reservoirs for separately owned reservoirs in series.

Upper Reservoir Diversion (cfs)	Lower Reservoir Diversion (cfs)	Total Diversion (cfs)
0	1,052	1,052
200	851	1,051
400	706	1,106
600	673	1,273
800	673	1,473
1,000	673	1,673
1,200	673	1,873
1,400	673	2,073
1,479	673	2,152

(e) The resulting trade-off curve (Figure A-61) shows that when these reservoirs act separately, the maximum total firm yield is developed when the diversion at Upper Reservoir is maximized (rather than when diversion at Lower Reservoir is maximized, as with coordinated operation), providing a firm yield 1,479 cfs at Upper Reservoir and a firm yield of 673 cfs at Lower Reservoir, for a total firm yield of 2,152 cfs. (These firm yields are the same as seen with these two reservoirs in parallel and operating separately.) Following the trade-off curve, as the diversion is reduced at Upper Reservoir, Lower Reservoir's firm yield remains at 673 cfs until

Upper Reservoir's diversion gets below about 550 cfs, at which point the yield at Lower Reservoir begins to rise. This turning point occurs because with diversion less than 550 cfs, Upper Reservoir begins to release some inflow to Lower Reservoir during Lower Reservoir's 1986 critical period, making a larger consistent diversion possible at Lower Reservoir. Since any Upper Reservoir firm yield between 550 and 1,479 cfs gives the same yield at Lower Reservoir, Upper Reservoir's firm yield should be defined as either between zero and 550 cfs, or as 1,479 cfs, but not any value in between, as that would represent a “waste” of firm yield capability at Upper Reservoir.

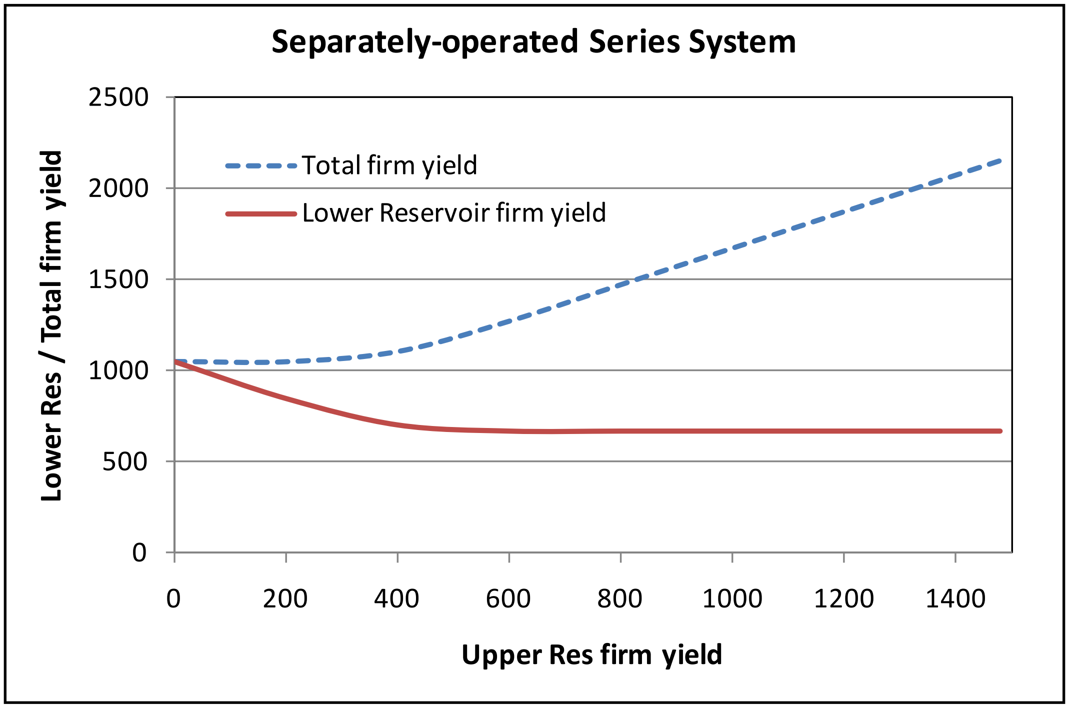

Figure A-61. Series system of two reservoirs, operated separately.

(f) To summarize the computation of firm yield for a separately operated system of reservoirs in series, the multi-step analysis approach just described involves making two opposite assumptions: full diversion of firm yield at upstream reservoirs, and then no diversion at upstream reservoirs.

- First, evaluate firm yield for the upstream reservoir, then divert that firm yield at the upstream reservoir and determine resulting firm yield at the downstream reservoir. This result is considered a minimum firm yield for the downstream reservoir.

- Next, assume no diversion at the upstream reservoir, and compute firm yield of the downstream reservoir. This result is considered the maximum downstream firm yield. (Note that this second step perceives no use of or benefit from upstream storage.)

- The third step is a trade-off analysis, decreasing diversion at the upstream reservoir and computing the resulting increased firm yield at the downstream reservoir. The eventual firm yield specification for the reservoirs involves choosing a value between the minimum firm yield of the first step and the maximum firm yield of the second step, considering the total yield and perhaps other system information such as location of water users.

(g) As with the analysis of jointly owned reservoirs in series, this procedure can be followed with three or more reservoirs, with more combinations of diversions needed for complete evaluation.

d. Storage accounting in Reservoir Systems.

(1) Thus far, when evaluating multiple reservoirs, a firm yield for the entire Conservation Pool of each reservoir has been determined. Further, only the current Conservation Pool size of each reservoir is being considered. Recall that when evaluating single reservoirs, storage/yield curves were computed. Two types of curve were defined: (1) a storage/yield curve spanning various reservoir/pool sizes, and (2) a storage/yield curve for differing percentages of the Conservation Pool (to evaluate storage needs of individual users). Creation of these curves allows interpolation to the storage requirement for a specified demand. (It would seem simpler to minimize the storage capacity for the specified demand. However, for iterative simulation with a detailed simulation model, it is easier to maximize a continuous diversion for a specified storage capacity.) Development of either of these storage/yield curves is more complex for multiple reservoirs. A storage/yield relationship of type (1) based on total storage at multiple reservoirs would not be unique, because there are infinite ways to distribute storage capacity between the reservoirs, and those different distributions would provide a different firm yield, so this task is put aside at this point. Creation of type (2) storage/yield curves (the percent-of-Conservation-Pool yield for individual users) is more tractable and will be discussed here.

(2) To consider individual users in the Conservation Pool of a reservoir, when there are multiple reservoirs acting together to serve the water supply need, it could be more effective to define a storage account that spans the reservoirs that are able to serve a particular user. First, consider a parallel system of two reservoirs, shown in Figure A-54, with a single diversion below the confluence of the two reservoirs' releases. The storage account capacity is a percentage of the sum of conservation space in both reservoirs. The storage accounting is performed as it is with a single reservoir, with deliveries subtracted from the account and percent-of-inflow to each reservoir added to the account. (A storage account of a certain percentage of the total conservation storage of the reservoirs receives a certain percentage of the total inflow to the two reservoirs.) Deliveries might be made from either reservoir, and the choice does not affect the storage account. The choice from which reservoir deliveries are made is based on the balance rule between the reservoirs. Maximizing firm yield for a given percentage of Conservation Pool, and repeating that computation for the range of percentages, defines a percentage-of-pool versus firm yield relationship for a user below both reservoirs.

(3) Consider instead a series system of two reservoirs, as in Figure A-56, which act together. A user diverting from Upper Reservoir can be served only by Upper Reservoir, but a user diverting from Lower Reservoir is served by both reservoirs operating together. With this understanding, a storage account could be based on (and reside in) all reservoirs in the system above the user’s diversion point. As stated for a parallel reservoir system, storage accounting is performed for a series system in the same manner as for a single reservoir, with deliveries

subtracted from the account and percentage-of-inflow to each reservoir added to the account. (Again, a storage account of a certain percentage of the total Conservation storage at both reservoirs receives a certain percentage of the total inflow.) Also as with parallel reservoirs, the balance or tandem rule between the reservoirs defines how water is stored in the system, but the location of the water would not be relevant to the storage account. The water will always be at or above the reservoir from which the diversion is made, making it accessible to the owner of the storage account.

(4) For a user diverting from one reservoir in a system of parallel reservoirs, which operates as a system for purposes other than water supply, the storage account would be located in only the reservoir that supplied the use. However, the determination of firm yield requires analysis of the entire system and will be discussed in paragraph A-12.

A-12. **Interaction with Other Objectives**.

a. Reservoir Conservation Pools may be shared by various reservoir objectives or uses, including water supply (M&I or irrigation), hydropower, pool recreation, flow augmentation (for stream recreation, navigation, fish and wildlife or water quality), plant cooling, and others. With the exception of pool recreation, these purposes all require some kind of yield, or “consumptive” use of water that is supported by both inflow and storage. (Note: In this document, the phrase “consumptive” is relative to the reservoir, and refers only to the fact that the water leaves the reservoir. It is not intended to imply the legal definitions of consumptive use in water law.) The reservoir's Conservation Pool as a whole has a firm yield, which can be defined in various ways for various purposes. For water supply, firm yield is the highest consistent flow rate that can be provided. For hydropower generation, the firm yield is the maximum consistent power in kilowatts (a rate) or energy in kilowatt-hours, and the flow rate to achieve that generation is not constant, but instead is higher when reservoir level is lower. For augmentation to maintain some minimum instream flow rate, the yield might be stated as the minimum instream flow, but could make use of downstream local flows below the reservoir release.

b. Firm yield for a given reservoir use is often subject to constraint by other reservoir uses. Firm yield for a water supply use that was not constrained or impacted by other purposes (had the “highest priority”) would be significantly greater than firm yield for a water supply use that was instead subject to the fulfillment of another reservoir use. Firm yield can either be evaluated as the “highest priority” (including an estimate of its impact on other purposes) or it can be evaluated as a “lower priority” use, constrained by other uses. In this section, both situations will be considered.

c. Note: the discussion of priority of reservoir uses in this chapter is to aid discussion of the yield analysis method and the modeling it requires. For example, when analysis considers a new use and must determine its impact on existing uses, the existing uses must be evaluated first as a higher and then as lower priority than the new use. Also, in the HEC-ResSim modeling used in the firm yield analysis, it is necessary to establish a rule priority structure in which the rules representing each use are arranged in a priority list. The discussion of priority here is not an implication that federal reservoirs establish priority between the various purposes served, or consider priority in operation of those reservoirs.

d. A first step in the analysis is to evaluate water supply firm yield in the absence of other reservoir uses or purposes. This process determines the firm yield the reservoir could provide if serving only water supply (or a similar "consumptive" Conservation storage purpose). Next steps are to consider other reservoir purposes in addition to the water supply firm yield, first as constraining and then as constrained by water supply (evaluated as "higher priority" or "lower priority" purposes, respectively). When another "higher priority" (constraining to water supply) purpose is included, the subsequent water supply firm yield is that which would be available with the other purpose satisfied to the level it was without water supply use. When a lower priority (constrained) purpose included, it should not impact the water supply firm yield, and the analysis is more a determination of the impact of water supply on the other purpose. This impact is evaluated at a later stage in the yield computation procedure, and higher priority (constraining) purposes will be discussed first.

e. The iterative simulation approach discussed in this document can be used to determine firm yield in multi-purpose reservoirs if the reservoir simulation tool can capture prioritized operating rules. However, the challenge in determining firm yield amongst other purposes is properly reserving water for the future. When water supply firm yield is evaluated alone, unused water remains in the reservoir for later use. When other "consumptive" purposes use water unused water that would otherwise be reserved for future use might instead be released for another purpose. This challenge will be discussed for additional constraining (higher priority) and constrained (lower priority) purposes, with storage accounts as a solution.

(1) Additional Purpose that Constrains Water Supply

(a) In reservoir simulation, "<u>non-consumptive</u>" reservoir purposes that are constraining to water supply yield can easily be captured, such as: flood operations, with a flood pool unavailable for storage other than flood detention; and, recreation, with a minimum pool below which there can be no water supply withdrawal. Since the satisfaction of these "non-consumptive" purposes is based on reservoir pool levels, it is simple for a simulation to discontinue the water supply use when necessary. To simulate this, water cannot be stored in the flood pool (except during a flood) and water cannot be withdrawn below the recreation level. Subsequent iterations would consider a smaller water supply diversion until finding the largest that would never be discontinued.

(b) "<u>Consumptive</u>" reservoir purposes can also be simulated as constraining to the water supply yield by stating them as a higher priority, for example: a downstream minimum flow requirement; or, minimum hydropower generation. Although these purposes use the same Conservation Pool as the water supply use, specifying them with higher priority will guide an iterative simulation modeling approach to satisfy these "operating rules" before the water supply rule, not just in each time period but for the entire period of record. To capture the situation correctly, the reservoir simulation tool used must respect the relative priority of various reservoir or system purposes as it determines reservoir releases. For the computations performed here, HEC-ResSim was used. HEC-ResSim's firm yield iteration tool is inherently able to respect higher priority rules when determining firm yield, due to both HEC-ResSim's native ordering of operating rules and the iteration tool's "rule test." After each iteration, HEC-ResSim checks for satisfaction of the minimum flow rule being maximized (the water supply diversion). Based on the rule priority structure, if a higher priority flow rule "fails" due to lack of water, because of the lower priority rule taking water at an earlier date, the lower priority rule (the water supply minimum flow rule) will also fail in that time period, causing the tool to reduce the threshold of the lower priority rule in the next iteration. HEC-ResSim will keep reducing the water supply rule in each iteration until the rule is exactly satisfied for the entire period of record, which thus ensures that all higher priority (constraining) rules are also satisfied throughout the period of record.

(c) As an example, the inclusion of constraining (higher priority) purposes in the reservoir operation will be represented by a downstream minimum flow rule of 500 cfs. In the absence of downstream local flows (below the reservoir but above the flow location), this need would be met by a consistent release of 500 cfs. In this case, a constrained (lower priority) water supply firm yield from a single reservoir would simply be 500 cfs less than firm yield in the absence of the constraining (higher priority) downstream rule. For example, for the single reservoir simulation shown in Figure A-22, with storage equals 400 KAF and firm yield equals 1,371 cfs, the 500 cfs downstream requirement would cause firm yield to decrease to 1,371 minus 500 equals 871 cfs. The storage and flow traces in Figure A-22 would appear the same, but destination of the outflow would be different.

(d) For multi-reservoir systems, the lower priority water supply firm yield might be as simple as 500 cfs less than without the downstream rule or might be more complex. As in paragraph A-11, parallel reservoirs differ from series reservoirs, and reservoirs that are operated as a coordinated system differ from those operated separately.

(2) Constraining Purpose Added to Parallel Reservoirs.

(a) In the parallel reservoir system explored in paragraph A-11 (shown in Figure A-54), a constraining or higher priority requirement of 500 cfs minimum flow is added below the confluence. In this system (as considered thus far), there are no additional downstream local flows above the diversion. For the case of coordinated reservoir operation to supply a single demand below the confluence, the firm yield was 2,454 cfs (operation shown with dashed green lines in Figure A-55). The addition of a 500 cfs downstream minimum flow requirement, with no additional downstream input, simply reduces the firm yield to 1,954 cfs. With additional downstream local flows included in the simulation, firm yield would be reduced less.

(b) For the case of the two reservoirs meeting separate demands at the reservoir sites (operation shown with solid red lines in Figure A-55), the addition of the 500 cfs rule applied to both reservoirs introduces a coordinated operation for the new rule, although still with separate operation to satisfy water supply firm yield. This situation is more complex than either separate or coordinated operation for water supply alone. The responsibility of each reservoir toward meeting the 500 cfs downstream requirement must be specified, before maximizing the firm yield of each for water supply. (This responsibility is often captured by specifying a desired reservoir volume balance.) By assuming a firm yield at one reservoir and diverting that amount, the firm yield at the other reservoir can be maximized subject to meeting the downstream flow. This maximization is less well-defined than the simple iterative simulation performed earlier, because varying the yield distribution between the reservoirs also requires varying the storage balance between the reservoirs to achieve operation in which both reservoirs reach empty once during the simulation. Table A-4 and Figure A-62 show the results of setting and diverting a specified firm yield at West Reservoir and maximizing firm yield at East Reservoir, then adjusting both along with system balance to achieve total use of storage volume. Note: With diversion from the reservoir pools, firm yield cannot be any larger than the at-site firm yield obtained by the reservoirs acting alone for only water supply, so a firm yield of 1,479 cfs at East Reservoir and 673 cfs at West Reservoir defines the bounds of the trade-off.

(c) Table A-4 and Figure A-62 contain firm yield at each reservoir, the total firm yield of both, and the storage balance that achieved those values. For comparison, without the 500 cfs downstream minimum flow rule requiring some coordination between the reservoirs, the total at-site firm yield is 2,152 cfs (1,479 cfs plus 673 cfs). Reducing this amount by 500 cfs gives 1,652 cfs. As seen in Table A-4 (and the dashed blue line in Figure A-62), the total firm yield ranges from 1,652 to 1,744 cfs, showing that the partially coordinated operation to meet the downstream 500 cfs requirement allows the reservoirs to share the burden in an efficient manner (given the respective inflows) that costs the water supply purpose less than 500 cfs.

Table A-4. Maximized diversion, East and West Reservoirs in parallel, with a 500 cfs downstream flow requirement.

East Reservoir Diversion (cfs)	**West Reservoir Diversion (cfs)**	**Total Diversion (cfs)**	**Storage Balance**
1,071	673	1,744	
1,110	656	1,766	95 - 10%
1,276	508	1,784	50 - 50%
1,370	400	1,768	50 - 25%
1,443	300	1,743	10 - 65%
1,473	200	1,673	10 - 95%
1,479	173	1,652	

(d) Figure A-63 shows two different balance solutions; solid red lines depicting one "edge" solution of meeting the entire downstream requirement from East Reservoir (first row of Table A-4), which provides a firm yield of 1,071 cfs at East Reservoir and a firm yield of 673 cfs at West Reservoir (i.e., acting for only water supply at West Reservoir); and dashed greens lines depicting another solution of meeting the requirement from both reservoirs (fifth row of Table A-4) with storage balance that drafts West Reservoir more, providing a firm yield of 1,443 cfs at East Reservoir and a firm yield of 300 cfs at West Reservoir. Note that even in the first case in which East Reservoir meets the downstream flow requirement alone (in addition to developing its water supply firm yield) it receives some help from West Reservoir, allowing West Reservoir's releases to satisfy some of the downstream need. This assistance is possible because East Reservoir's critical period lasts several years, and so wet season releases from West Reservoir satisfy the downstream 500 cfs and allows East Reservoir to store more water during those times.

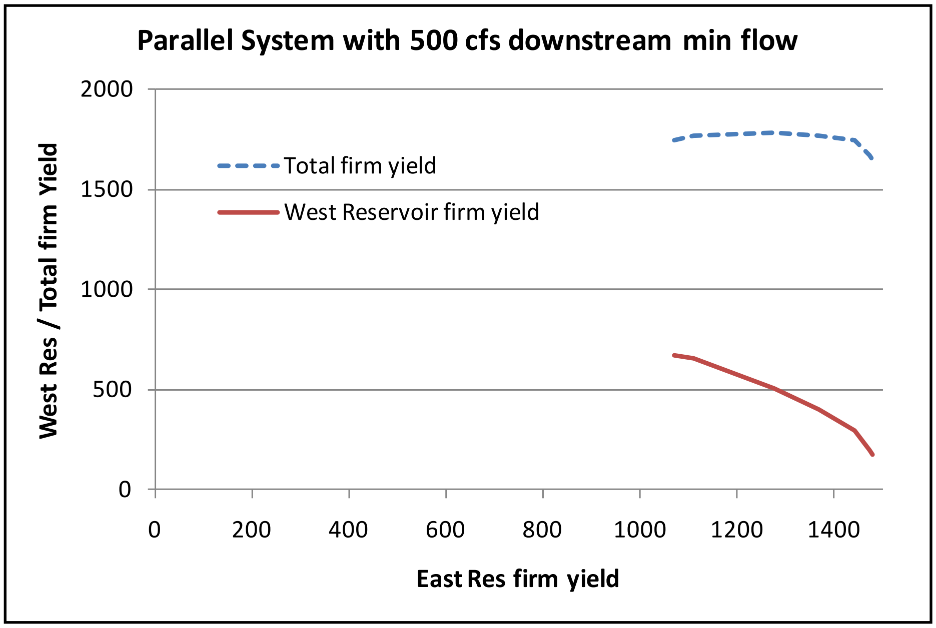

Figure A-62. Firm yield at West and East Reservoirs, sharing a downstream flow requirement of 500 cfs.

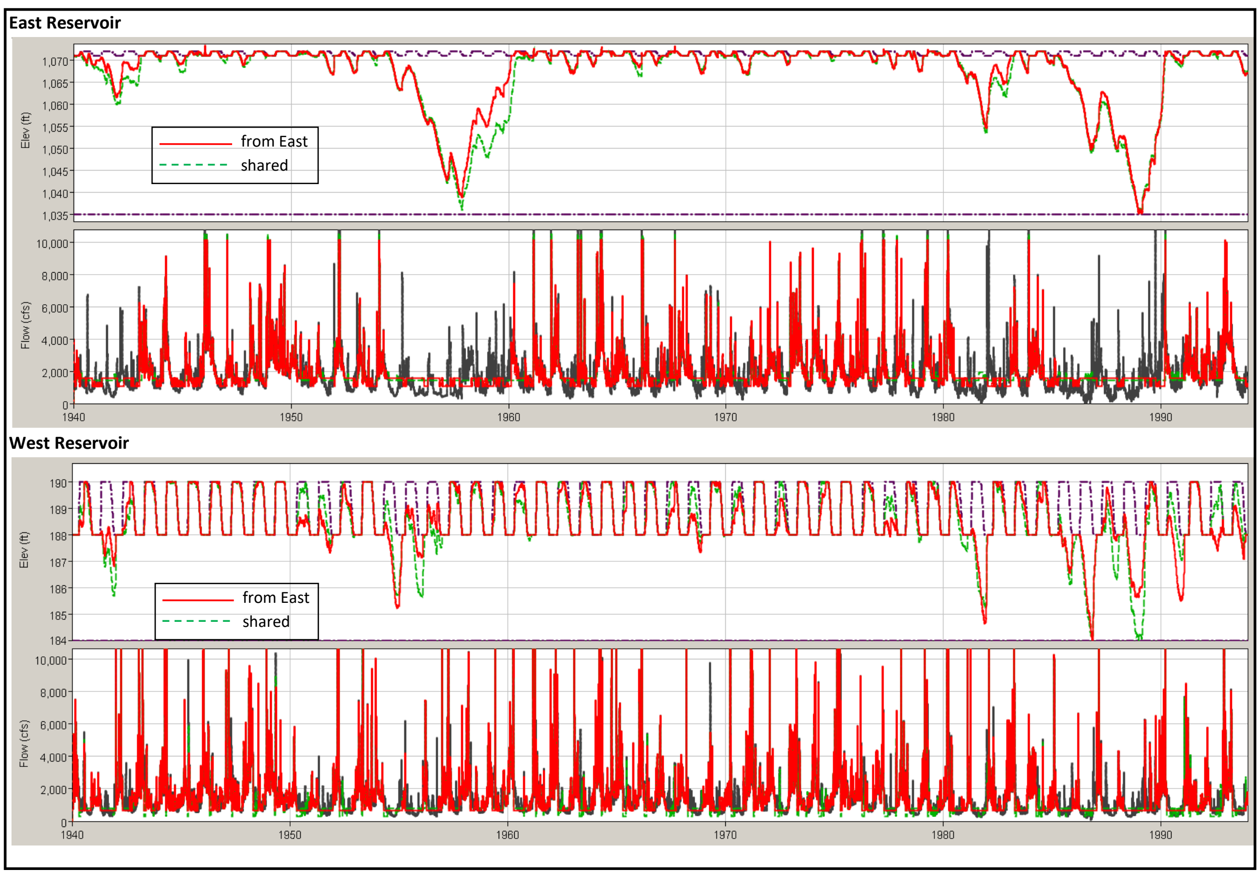

Figure A-63. Time-series plots of reservoir storage and inflow/outflow for two reservoirs in parallel, meeting downstream with a 500 cfs minimum flow from East Reservoir (red), and from both reservoirs (green).

(e) In contrast, the solution that meets the entire need from West Reservoir (last row of Table A- 4) gives storage traces at both reservoirs that are identical to when the two reservoirs act independently for firm yield (red lines in Figure A-55). East Reservoir is releasing solely for its firm yield of 1,479 cfs, and West Reservoir releases 500 cfs to downstream rather than yield, but still releases a consistent total of 673 cfs. The reason for this identical result is that West Reservoir's critical period is less than one year (1986), and during that time the reservoir does not receive assistance from East Reservoir in meeting the downstream requirement, as East Reservoir is releasing solely to firm yield during that period.

(f) Simulation to produce the partially coordinated operation of the parallel reservoir system (operating separately for at-site water supply and together for the minimum downstream flow) was not simply an automated iterative simulation, because of the need to specify an effective storage balance when varying the firm yield distribution between the reservoirs. However, given a specified storage balance, the iterative simulation could be automated.

(g) To summarize the computation of local firm yield at cooperative parallel reservoirs with a common constraining or higher priority use, firm yield is first computed for each reservoir acting independently and without the higher priority use (downstream minimum flow requirement.) Then the tradeoff relationship in Table A-4 is produced as follows.

- The downstream minimum flow rule is added to both reservoirs. The local diversion at one reservoir is first set at its independent firm yield and the local diversion at the other reservoir is maximized, adjusting the storage balance until both reservoirs empty once, producing one point on the trade-off curve.

- Next, the local diversion at the first reservoir is successively reduced, maximizing the local diversion at the other reservoir with adjustments to the storage balance, producing other points on the trade-off curve. When the second reservoir can achieve its independent firm yield, diversion at the first reservoir need not be reduced any further.

(h) Each solution is a potential choice of the firm yield for both reservoirs. The choice might be the maximum total or might be chosen based on the location of water users. The procedure can be followed for three or more reservoirs as well, with a much larger combination of runs to produce the trade-off analysis.

(3) Constraining Purpose Added to Series Reservoirs.

(a) In the series reservoir system explored in paragraph A-11.c. (Figure A-56), the constraining or higher priority requirement of a 500 cfs minimum flow below the downstream reservoir is added. In this system (as considered thus far), there are no additional downstream local flows. For the case of coordinated reservoir operation with water supply diversions at both reservoirs, the maximum total yield was 2,454 cfs with diversion only at Lower Reservoir, decreasing as the diversion at Upper Reservoir is increased (Table A-2 and Figure A-59.) The addition of a 500 cfs downstream minimum flow requirement to the diversion only at Lower Reservoir, with no additional downstream input, simply reduces the yield to 1,954 cfs. For other distributions of firm yield between the reservoirs, as shown in Table A-2 and Figure A-59, the total firm yield is also reduced by 500 cfs. With additional downstream local flows included in the simulation, firm yield would be reduced less.

(b) When operation is not coordinated between the two reservoirs, a first glance shows Lower Reservoir bearing the burden of the downstream flow requirement. Or, if Upper Reservoir did release to the downstream minimum flow requirement, Lower Reservoir would intercept that water, and have to deliberately pass it through. An operation rule could allow Upper Reservoir to release half of the required downstream flow (or some other fraction), releasing that water to Lower Reservoir which would then release the entire downstream requirement. In this fashion, the burden would be shared, and operation would be coordinated only for the purpose of the downstream 500 cfs flow. Efficient coordination that took advantage of the respective reservoir inflows would make sense and would require more careful sharing.

(4) Additional Purpose Constrained by Water Supply.

(a) When using HEC-ResSim for reservoir simulation, it is currently more difficult to capture the impact on an additional reservoir purpose that is subject to satisfying water supply, rather than constraining to water supply yield. Unless horizontal reservoir zones (pools) are specified, with constrained or low priority purposes not included in lower-elevation zones, HEC-ResSim does not explicitly conserve water for future use by one purpose rather than another (in this case for water supply). If the "lower priority" purpose is stated as a release rule, it can detract from future "higher priority" water use by using water in the present. In other words, in a reservoir zone having release (or generation) rules for multiple purposes, HEC-ResSim will supply all of those needs when water is available; if at a later time the reservoir does not have water to supply all needs, HEC-ResSim will cut the lower priority first, but soon afterward the higher priority purpose will fail as well. (Note: This outcome is captured in HEC-ResSim yield simulation when the additional use is higher priority, because the water supply rule being maximized would fail, and spur the next iteration with a lower diversion rule until it did not fail during the simulation, meaning the higher priority use did not fail either.) USACE guidance in past decades recommended definition of horizontal zones to create a separate, lower reservoir pool in which the lower priority use is discontinued or cut back (see example in USACE, 1967). However, this approach does not allow the flexibility of operation sought here. Reserving some volume for a higher priority purpose in a shared pool requires water or storage accounting, with the ability to define a storage account belonging to the higher priority purpose, holding water that is only for use by the higher priority purpose, which may provide greater flexibility in operations.

(b) The inclusion of a constrained or lower priority purpose in a yield analysis is generally done to determine the impact of changing the water supply allotment. This impact might be (1) a reduction in overall satisfaction of the constrained (lower priority) purpose, or (2) a reduction in firm yield of that purpose. When considering the first impact, to properly simulate the impact of water supply yield on a constrained (lower priority) purpose, the constrained purpose must occasionally fail, while the water supply rule (diversion) continues to be met at the specified level. With storage accounting enabled, if the only stored water in the reservoir pool belongs to another purpose (either higher or lower priority), leaving no water available for the purpose in question, that purpose's use of water must be curtailed. This limit would be imposed based on allocated volume, rather than the elevation of the reservoir. Storage accounts have been described as vertical or floating pools because a water user can store their water volume (storage account) anywhere in the Conservation Pool, and can access that water volume whether the pool is otherwise full or nearly empty. (The only limit to accessing a storage account would be due to the diversion facilities, and whether it is physically possible to divert water.) With storage accounting performed by the reservoir simulation model, the firm yield of water supply could be ensured, while the lower priority uses would be supplied as often as possible, and comparison to simulations without (or with lower) water supply release would demonstrate impact.

(c) For constrained (lower priority) uses that can be satisfied without operating rules, such as secondary hydropower generation, a simple computation of the constrained use with the water supply diversion satisfied will demonstrate the impact on the that use. Storage accounting would not be needed in this case, because in the simulation environment the lower priority use would not be able to "take" water, but rather only makes use subsequent releases.

(d) If the reason for inclusion of the constrained (lower priority) purpose is the second impact above (reduction in firm yield of that purpose), then to determine the purpose's firm yield (i.e., a service rate that would not be interrupted during the period of record) as impacted by a water supply firm yield, the exercise is performed for water supply allotments smaller than the firm yield of the entire Conservation Pool. Otherwise, as the water supply firm yield diversion brings the reservoir pool to empty during the critical period, no lower priority purpose could have uninterrupted use. Instead of simulating a single water supply diversion, a trade-off analysis can be performed with successive reduction of water supply diversion and the subsequent increase in a consistent level of the constrained purpose, plotting several points of tradeoff. The resulting trade-off curve would capture the relationship between water supply firm yield and the firm yield available to constrained (lower priority) uses.

(5) Complementary and Conflicting Water Uses.

(a) Overall yield of a reservoir is the provision of water for different purposes, many of them "consumptive" uses (from the perspective of the reservoir). Sometimes a reservoir release benefits several purposes at once, such as a release that generates hydropower, satisfies an in-stream flow requirement, and then is diverted downstream for M&I use. Other purposes of the reservoir may be in conflict, such as an M&I diversion from the pool that would not pass through hydropower turbines or the river downstream, nor remain in the reservoir to serve pool recreation. If the various purposes were each assigned their own storage account, they could each make use of their reserved water to meet their needs. This accounting would be helpful for purposes in conflict, as each would have their own water reserved to use when needed, and that water could not be removed by other purposes. But for purposes that are cooperative, we must consider assigning the responsibility or account deduction for releases. Which purpose would spend water for the release from its own storage account, and which purpose gets use of the water without cost?

(6) This issue is one of storage accounting, but can impact the computation of firm yield, which would therefore impact both the size of storage account required for each purpose, and whether that specified account was in fact adequate during future dry periods. For example, if streamflow augmentation was determined to be the last use to expend its water for a release, the firm yield computation for that purpose, based on a specified capacity of storage account, would draw from its storage account only when no other reservoir release satisfied the downstream flow need. At all other times, when other uses release water to the river, no volume would be spent from the flow augmentation storage account. Likely, the only time the augmentation storage account would be spent is when other uses have depleted their own storage accounts and are unable to provide water for release. Only at those times would the flow augmentation account have to expend its account water to supplement downstream flow. The result of being "last in line to be responsible for release" would result in a seemingly larger firm yield for a given storage account, or a smaller storage account needed to ensure a defined minimum in-stream flow.

(b) This document notes the issue of defining the responsibility to supply released water from a storage account when there are multiple storage accounts in a reservoir, but does not offer a solution. The decision would differ by system and region. However, this is an important issue that should be discussed between USACE and other reservoir stakeholders. Currently, when using HEC-ResSim to evaluate such storage accounting, the tool will deduct water from the storage account associated with the highest priority rule (within ResSim's rule priority definitions).

A-13. **Summary and Conclusions**.

a. This document has described and summarized methods for storage/yield analysis in reservoirs, shared reservoir pools, and multi-reservoir systems. The end use that prompted this study is determination of the reservoir storage volume required for water supply user agreements, in which a water user contracts for some volume of storage space within a USACE reservoir, to store water for their own use to provide a firm yield for a given water supply need.

b. Storage/yield theory is essentially a determination of the need to store water for future use in order to meet a given demand for water, hydropower, water quality, or other purpose. This document first describes traditional methods that define storage requirement as the maximum cumulative deficit between streamflow and demand over a period of record. Periods of deficit require water from storage to satisfy demand, and the maximum cumulative deficit is therefore the amount of stored water needed to satisfy demand during that dry period. The demand (consistent release) specified is termed the "firm yield" and the period of time that experiences the maximum deficit, and so defines the firm yield, is termed the "critical period." It is noted that different levels of demand requiring different storage volumes might have different critical periods, making it essential that yield methods evaluate either the entire period of record or all of the potential critical periods. (Thus, it would seem important for firm yield estimates to be stated along with the period of record used in the analysis, and the relevant critical period within it.)

c. The iterative simulation method for yield analysis was next described as an approach that can capture more detail in the aspects of reservoir storage and operation that affect firm yield. With this method, the problem is reversed from determining the storage requirement for a specified release (demand) to determining the maximum consistent release (firm yield) provided by a specified storage capacity. The reservoir simulation is iterated with successive approximations of release for demand to determine the maximum consistent release that can be satisfied without failure, i.e., the release that exactly empties the reservoir storage volume once during the period of record. This maximum release is the firm yield for the simulated storage capacity. Simple mass-balance simulation provides the same result as traditional simple methods discussed above, and more sophisticated simulation can provide a more accurate result that considers reservoir losses and gains, seasonal reservoir pools, multiple reservoir purposes and priorities, and interaction with other reservoirs and downstream flows. <u>This ability to capture more accurate detail makes iterative simulation the recommended approach for yield analysis.</u>

d. The above methods for determining firm yield of a reservoir volume (the Conservation Pool) can also be used to determine the firm yield of some portion of a shared reservoir Conservation Pool. Analysis of yield in a shared pool differs from analysis of the total pool because a user with only a share of the storage pool receives only a share of the reservoir inflow. Inflow apportionment can be complex, and so the simpler case is used for example here, assuming a user receives a certain percentage of inflow when allocated that percentage of the Conservation Pool. Computation of the firm yield of some portion of the storage capacity must therefore track the inflow credited to the water supply user's storage account, and the user's withdrawal or release from that account to meet a water supply demand. This tracking is referred to as "storage accounting" and the user's storage capacity is termed a "storage account." Any of the yield analysis methods discussed above can treat a storage account in the same manner they would treat a reservoir storage pool, determining either the storage account capacity needed to supply a specified demand (using simple methods), or the maximum consistent demand that can be satisfied from a storage account of specified capacity (using the iterative simulation method). Further, simulation of a storage account within a model that simulates the entire reservoir or system of reservoirs can capture details of the storage accounting affected by the reservoir state (such as losses and gains), and reservoir operation for other purposes. <u>Iterative simulation of a storage account within a reservoir model is therefore the recommended method for yield analysis for water use contracts.</u>

e. The iterative simulation approach can also determine the firm yield of a multi-reservoir system. The arrangement of reservoirs within the system (parallel, series or both), and whether or not the reservoir are operated with common goals, determines the simulation analysis approach needed to define firm yield for the system as a whole or for the individual reservoirs. Analysis approaches were described for the various system configurations and levels of coordinated operations, with a simple example used to demonstrate them.

f. The analysis techniques for multi-reservoir systems were demonstrated for evaluating firm yield of the entire Conservation Pool of each reservoir. To consider a user utilizing only a share of the total Conservation space, storage accounting as described for single reservoirs can also be applied within jointly operated multi-reservoir systems and is performed in the same manner. The storage account can reside in all reservoirs that are above (and therefore can supply) the water user's diversion site and that storage account's capacity is all or some portion of the total Conservation storage at all reservoirs.

g. Another benefit of the iterative simulation approach over the traditional simple methods of yield analysis is the ability to represent a reservoir or system operating for several purposes with different priorities. Higher priority purposes affect the firm yield available to water supply, and lower priority purposes are in turn impacted by water supply use. The ability of a reservoir model to simulate prioritized operating rules allows computation of water supply firm yield with higher and lower priority purposes. This document describes the analysis approaches for using iterative simulation of such a reservoir model to consider firm yield amongst other uses. Simulation of a storage account is needed to consider other reservoir purposes within a shared Conservation Pool.

h. This document includes discussion of the reliability of firm yield because there is no true expectation that the driest period in the observed streamflow record, which defines the firm yield, is also the worst that will be experienced in the future. Reliability methods are described; however, no recommendations for required reliability are made at this time.

i. The firm yield methods described in this document address the issues of water supply use within multi-purpose USACE reservoirs. The recommended method to define firm yield of a reservoir, shared reservoir pool, or reservoir system is iterative simulation, including a storage account defined for water supply use. Many situations were described, with examples provided. The same techniques that evaluate firm yield for water supply can be used for firm yield of any reservoir purpose that consumes water from the reservoir, such as hydropower or flow augmentation for navigation or fish and wildlife.

APPENDIX B

Abbreviations

BOD: biochemical oxygen demand

CE-QUAL-W2: two-dimensional, vertical-longitudinal, hydrodynamic water quality model for rivers, estuaries, lakes, reservoirs, and river basin systems

CDF: cumulative distribution function

cfs: cubic feet per second

EC: Engineer Circular

FCSDR: Flood and Coastal Storm Damage Research and Development Program

HEC: Hydrologic Engineering Center

HEC-5Q: Hydrologic Engineering Center's HEC-5 Simulation of Flood Control and Conservations Systems; Water Quality Analysis software

HEC-ResSim: Hydrologic Engineering Center's Reservoir System Simulation software

KAF: kilo (1,000) acre feet

LP: linear programming

M&I: Municipal and Industrial

R&D: Research and Development

U.S.: United States

USACE: U.S. Army Corps of Engineers

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APPENDIX C

Glossary

Conservation Pool: Elevation zone in a reservoir dedicated to water storage.

Critical Period: Period of time that experiences the maximum deficit in a water use.

Deficit: Condition when available supply (streamflow) is less than demand.

Demand: Flow rate required for some water use.

Firm Yield: Demand (consistent release); largest consistent flow rate that can be provided throughout a period of record of streamflow.

Flood Pool: Elevation zone within a flood control reservoir that is available for storing flood flows and maintained as empty otherwise.

Guide Curve: Target elevation; rule curve.

Kurtosis: The thickness of probability distribution tails.

Maximum cumulative deficit: The amount of stored water needed to satisfy demand during a dry period.

Prior Appropriation Water Law System: Water rights system in Western United States; water rights are unconnected to land ownership and can be sold; the first person to use a quantity of water from a water source for a beneficial use (agricultural, industrial, ecological (only some jurisdictions), household) has the right to continue to use that quantity of water; subsequent users of the water source can use the remaining water provided they do not infringe on the rights of previous users.

Riparian Water Law System: Water rights system in Eastern United States; all landowners whose property is adjoin to a body of water have the right to make reasonable use of the water; when supply is low allotments are generally fixed in proportion to frontage of the water source.

Rippl Mass Diagram: Graphical method for estimating storage required to meet a constant demand; compares an accumulation of inflow over time to accumulated demand; restricted to evaluating a constant demand.

Sequent Peak Algorithm: Method for estimating storage required to meet a constant demand; derives the largest deficit volume of a discharge series for a reservoir with respect to a certain threshold level.

Surplus: Condition when available water (streamflow) is in excess of the requirement.

Storage account: Storage capacity that is allocated for one user or purpose within a multipurpose and/or multiuser reservoir. Also called "water account."

Storage accounting: A systematic process of quantifying, identifying, recognizing, reporting, and assuring information about water, the rights and other claims to that water, and the obligations against that water. Also called "water accounting."