United States Department of Agriculture

Soil Conservation Service

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20013

July 15, 1991

TECHNICAL RELEASE NO. 75
210-VI

TR-75

SUBJECT: ENG - RESERVOIR STORAGE VOLUME PLANNING

Purpose. To distribute Reservoir Storage Volume Planning (RSVP) computer program instructions.

Effective Date. Effective when received.

Background. Selecting appropriate storage and release rates for reservoirs is essential to sound water management. A significant number of impoundments, operated for single or multiple purpose use in the United States, lack adequate reservoir operation guides and tools to guide this process each year. A methodology has been developed by the Soil Conservation Service to improve management capability at many of these reservoirs.

The technique involves generating a family of volume-outflow curves for each forecast period. These curves permit operators to use predicted inflow volume to set outflow rates that will enable them to reach a full reservoir after passage of the seasonal peak. Forecasts at three probability levels help establish the range of likely seasonal runoff events. The volume-outflow curves provide an operational tool useful for effective water management of reservoirs where forecast information is available. The suggested contents of a reservoir operation guide will be in the National Engineering Manual.

Enclosed for your use is the rationale for volume-outflow curve development and a description of a system (collection of programs) available to produce them. Appendix A provides an example along with a rule curve technique allowing operational goals to be interfaced with the volume-outflow curves. Technical specialists with water resource management responsibilities should acquaint themselves with this system. Any questions regarding application of the RSVP system which is a part of the Centralized Forecasting System (CFS) should be directed to the Water Supply Forecasting Staff at the WNTC.

-MORE-

Filing Instructions. File with other Technical Releases.

Distribution. These instructions should be made available to SCS engineers with an interest in reservoir operation studies. States should make copies of these instructions available to other Federal, state, and local agencies in their area who may be interested. Copies will be distributed from the National Headquarters to Federal agencies at their national office level.

Comments or problems relating to computer program use or instruction should be sent to the WNTC.

Additional copies may be obtained through the Consolidated Forms and Publication Distribution Center by ordering TR-75.

EDGAR H. NELSON
Associate Deputy Chief
for Technology

Enclosure

DIST: TR-75 (refer to next page)

U.S. DEPARTMENT OF AGRICULTURE
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NHQ-ADS-012
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Introduction

Annual water supply in the Western U.S. is highly variable, often fluctuating dramatically between extremes. This inherent natural variability imposed by climate and geomorphology makes it difficult for water managers to plan their reservoir operation to use available runoff optimally. The seasonal nature of runoff also complicates management because most flow generally occurs in a four-month period (April-July typically). This snowmelt produces from 50 to 85 percent of the region's annual runoff.

Many water users have found it necessary to construct reservoirs that enable them to capture seasonal flow volumes and regulate releases. Additionally, some reservoirs are large enough to provide significant carryover storage, thereby minimizing the effects of dry periods. The water held in storage in these reservoirs is used for irrigation, hydropower production, municipal and industrial water supply, flood control, fisheries, recreation, or a combination of these uses. Often there is competition among uses, making it important for managers to use the best analytical tools available to fill and empty reservoirs in a manner which maximizes water use.

In most cases, reservoir capacities are significantly smaller than average annual runoff. As a result, managers are required to balance storage and releases with expected inflow volume. To aid them in this task, seasonal streamflow volume forecasts are issued by the Soil Conservation Service (SCS) and/or the National Weather Service (NWS).

For reservoirs that depend on seasonal runoff for all or a portion of their inflow, a system has been developed to help managers set outflow, enabling them to meet storage goals. The technique is principally oriented toward operation and management of reservoirs having less than 100,000 acre-feet useable capacity and whose primary function is to provide storage for agricultural, municipal, flood control, or recreational interests. This Technical Release (TR) describes the generation of "volume-outflow curves" and "rule curves" that permit managers to use anticipated inflow volume to target outflow rates in order to reach defined storage levels. The theory used to construct the curves is presented first, and then a mathematical algorithm is described which produces the curves objectively. Next, a system that incorporates the volume-outflow curves algorithm, data input, data analysis, and curve plotting is explained; followed by an example application of the rule curve technique in conjunction with water supply forecasts. Finally, appendix A goes into further detail in use of the Centralized Forecasting System (CFS), RSVP, and incorporation of operational goals through development of rule curves.

Basic Concepts

Melting winter snowpack and spring and early summer rain are the primary sources of water in many locations. Flows from these sources into a reservoir vary significantly from year to year and from day to day within a given year, depending on a number of factors. These include the volume of water accumulated in the winter's snowpack, basin soil wetness, areal extent of snow cover, temperature conditions during the main snowmelt period, and the amount and rate of spring and early summer precipitation. Reservoir managers must assess these factors and the uncertainty they impose in terms of risks associated with storing too much or too little water. To the degree that they can reduce uncertainty about future runoff, managers incrementally reduce their exposure to risk. An analytical tool is needed to help them define the magnitude and probability of runoff events several months in advance and the consequent implications for project regulation.

Ideally reservoir operation should regulate outflow to minimize spilling excess water; satisfy downstream water uses; minimize downstream flooding; provide sufficient water for recreation, fisheries, and wildlife; and enable the reservoir to be full near the end of the highest runoff. Sometimes, heavy snowfall or rain occurs in late spring and may prevent the achievement of ideal outflow conditions each year to satisfy all of these requirements. However, most of the time, the manager can successfully base each year's reservoir operation on expected runoff conditions by using water supply predictions. During heavy snowpack years, downstream flooding can be reduced; and in low snowpack years, the effects of low runoff can be somewhat moderated. In all situations, the main purpose(s) of reservoir operation is to assure that water users' interests are not compromised.

Typically, snowmelt runoff begins on most streams from late March to early May, with the recession continuing into July or early August. Peak inflows usually occur between mid-May and early June. Although this flow pattern is repetitive, in total volume and timing of runoff show substantial variability making it necessary for reservoir managers to tailor their operations to prevailing conditions.

Examination of runoff hydrographs on snowmelt-dominated streams has revealed that on an individual gaged watershed, the hydrograph shape and time distribution are consistent. This implies that it is possible to construct a relationship between seasonal volume and reservoir outflow settings to achieve a specific storage goal. Seasonal volume serves as an index to hydrograph shape. Relationships can be developed for any period for which forecasts are made; e.g., March-July, April-July, April 15-July 31, May-July, June-July.

Specifically, a relationship is desired for each forecast period so that a reservoir manager can select an outflow that would produce a specified storage level if the forecast seasonal runoff actually occurs. Figure 1 illustrates conceptually how an operator would use volume-outflow curves derived from gaged inflows to a reservoir. In actual practice reasonable minimum (RMN), and reasonable maximum (RMX) forecasts are often expressed as percent of average. Entering the graph with the forecast values and moving horizontally to the remaining volume produces a range of outflow. The outflow chosen is based on an assessment of local operating constraints and magnitude of runoff expected. This allows the reservoir manager to meet the objectives while maintaining fairly constant release rates.

Figure 2 helps illustrate how adjusting outflow rates based on the forecast affects reservoir levels and outflow. For example, assume that the March 1 forecast indicates that the reservoir, which is a little under half full, is at a satisfactory level for the forecasted spring runoff. Outflow (1) during March is set equal to inflow so there are no significant increases or decreases in storage.

April 1 forecasts are received. After entering April-July volume-outflow curves with the forecasts and desired storage, it was decided to set the outflow equal to the value shown as (2). In figure 2, the outflow remains constant until May 1 forecasts are received. The May 1 forecasts, May 1 storage, and the May-July volume-outflow curve indicate that a higher outflow setting is needed. Gates are opened to a new outflow value (3) in early May.

The May 15 snow survey data and May 15 storage indicate that a higher outflow is needed. Gates are opened to a new outflow (4) after mid-month when revised forecasts are received. The volume of water staying in the reservoir as storage is represented by the cross-hatched area (5). The stair-step effect of increasing outflow reflects adjustments made consistent with new forecasts and other hydrometeorologic data.

On June 28 (6), the reservoir is filled and outflow is set to equal inflow. This could be sooner or later, whether depending on whether it is a low, average, or high snow year and spring precipitation is below, near, or above average. Outflows equal inflows (7) until irrigation demands exceed inflow; water is then released from storage (8) to satisfy demands through the irrigation season.

Besides determining outflow rates during the main runoff period, early-season forecasts and volume-outflow curves can be used to determine desirable storage levels in the reservoir. When the present storage and forecasted runoff indicate an outflow less than that needed for downstream uses, it is desirable to increase storage prior to spring runoff. The storage level that is desirable could be determined by reading the storage at the intersection of the forecast and the desirable outflow.

Figure 1. Typical volume-outflow curve.

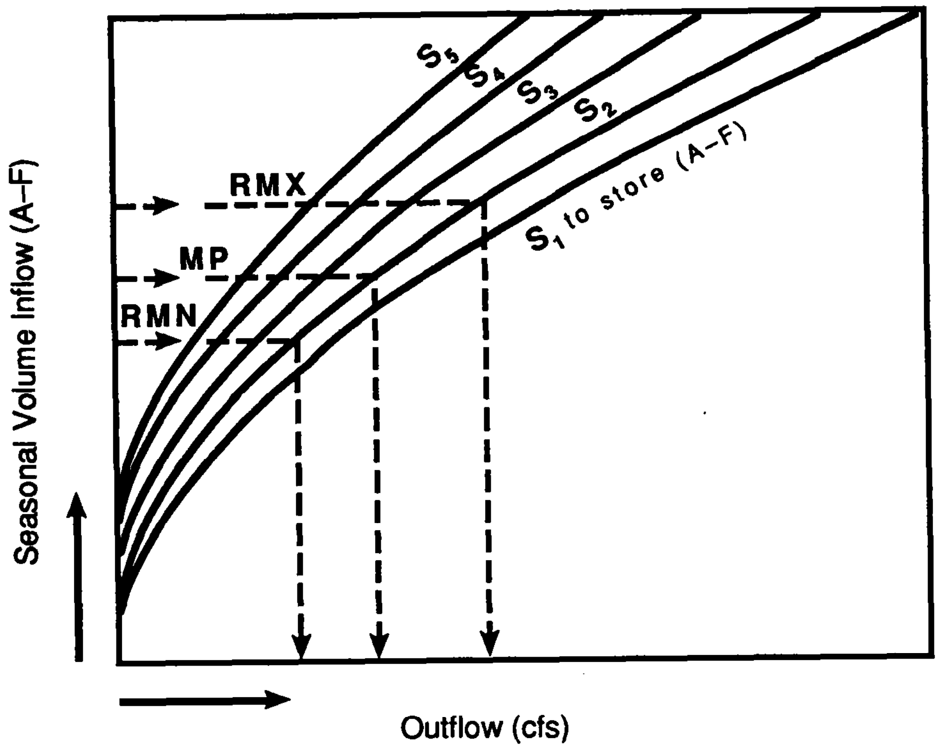
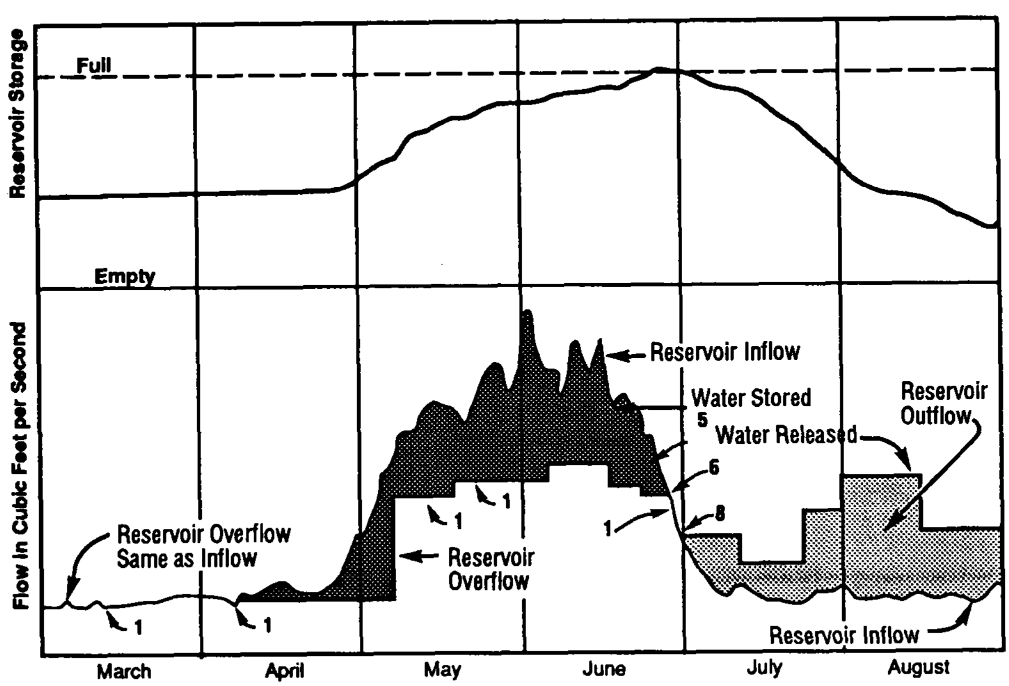


Figure 2. Typical reservoir season.



Volume-Outflow Curve Development

Development of volume-outflow curves in figure 1 is unique for each reservoir and can be done either manually or with a computer. The manual method is described first because it will enable the reader to understand more fully the approach taken and will lead to a better understanding of how the computer program accelerates the task. The first step is to obtain a minimum of 10 years of daily reservoir inflow data. This data set should include high and low runoff conditions and should not be overly biased toward the maximum or minimum. Daily streamflow observations for the snowmelt period will satisfy the minimum data requirements. However, complete annual records are desirable to detect unusual runoff events that affect reservoir operation but are unrelated to snowmelt runoff.

For each of the years included in the analysis, individual storage versus outflow curves are constructed by selecting a series of outflows and tabulating the corresponding storage for the given seasonal inflow hydrograph. Storage volumes are the sum of all daily flows greater than or equal to the selected outflow. This prevents a loss of storage and implies that the outflow is set equal to inflow when the outflow is higher than inflow. The storage-outflow data pairs are then plotted and a smooth line fitted to the points either by eye or a least squares analytical method. Figure 3 illustrates this procedure for a typical year's hydrograph. Setting outflow rates of 0_A, 0_B, 0_C, 0_D results in storing volumes S_A, S_B, S_C, S_D (cross-hatched area). In actual practice, many more points than four are generated to fit the storage-outflow curve. Figure 4 shows examples of six storage-outflow curves for a hypothetical 6 years of record stream based on April-July daily inflow data. High, low, and intermediate seasonal volumes are represented. From these relationships, volume-outflow curves can be created for specific storage levels.

This is accomplished by generating a series of seasonal volume-outflow rate data pairs for a range of storage levels, (S_1 in figure 4) and fitting a smooth curve to the points. To generate the pairs, select a desired storage level and, for each year, read the outflow setting required to produce it from the curves of figure 4. Doing so for a storage increment of S_1 results in outflow 0_1, 0_2 ...0_6 for each year. Data pairs consisting of these seasonal volumes and associated outflows are plotted and a line is fitted to the points either visually or using a curvilinear least square regression technique. Figure 5 shows a volume-outflow curve for the S_1 storage increment derived from the graphs of figure 4. Successive repetitions of this procedure for other storage increments produce a family of volume-outflow curves, such as those of figure 1. Families of curves for other seasonal flow periods can be developed by the method outlined.

Figure 3. Storage-outflow curve for a typical year.

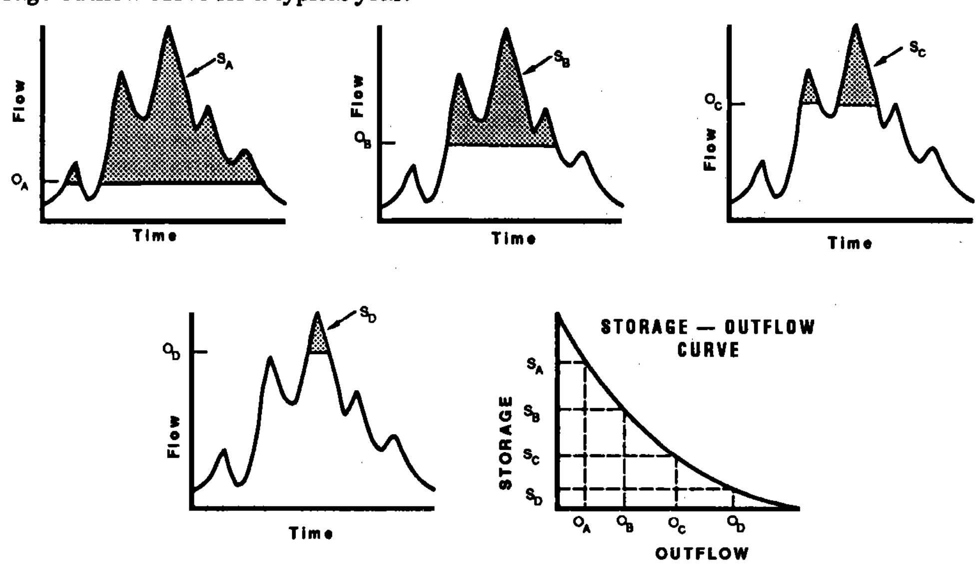


Figure 4. Storage-outflow curves for a period of record.

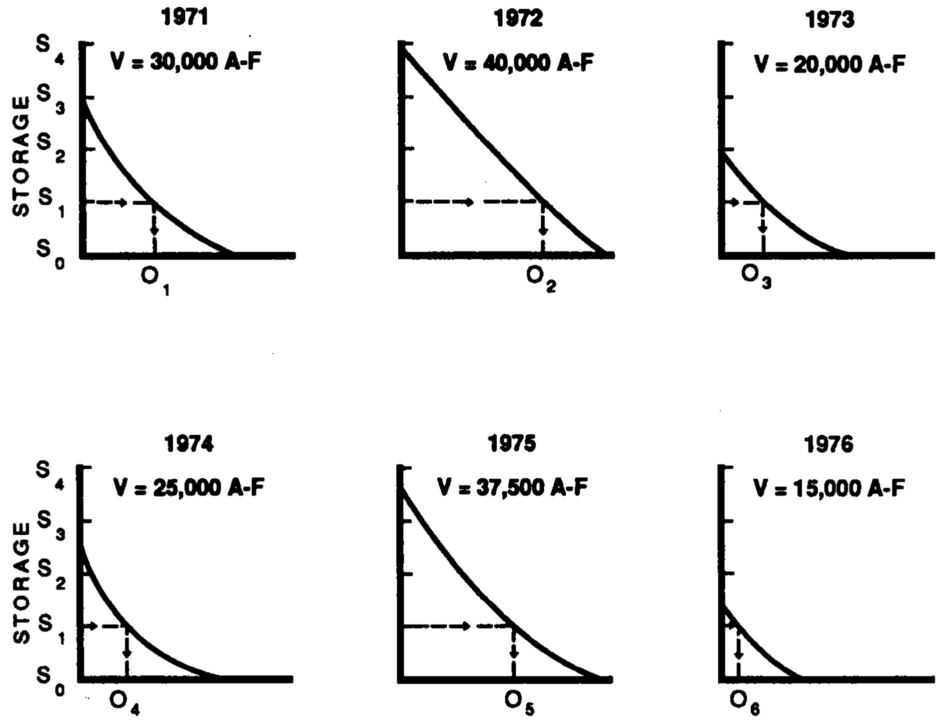
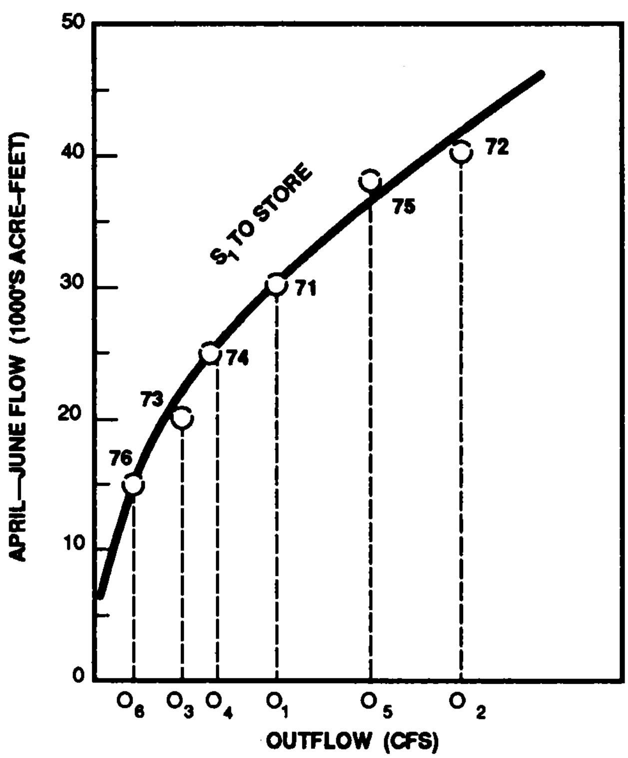


Figure 5. Typical Volume-outflow curve for one storage level.



Volume-Outflow Curve Algorithm

Building on this concept of volume-outflow curve development, an automated technique can be used to produce the family of curves. The volume-outflow curve algorithm to generate the curves is an analytical least squares fit of a three-dimensional data set consisting of seasonal inflow volume, outflow rate, and storage level. The selected regression model relating these variables is:

$$V - S = a_1(O) + a_2(O)^{0.5} + a_3(O)(S) \quad (1)$$

where V = total seasonal volume inflow to reservoir;
S = desired storage;
O = outflow required to obtain desired storage;
and a_1, a_2, a_3 are all regression coefficients

The transformed variables were chosen to meet certain rational or observed behavior. The dependent variable, V-S, was chosen so that when the outflow setting was at or near zero, the predicted storage level would be at or near the inflow volume; i,e, S = V when O = 0.0

The first independent variable was set as a standard linear regression term. The second independent variable $(0)^{0.5}$ was set to reflect the observed curvature behavior between inflow volume (V) and outflow setting (0) for a given storage (S). The third independent variable (S)(0), was chosen to reflect the skewness between the various storage level curves. The coefficients a_1, a_2, and a_3 are found by solving the normal equations dictated by the form of the model (McCuen, 1985). These equations are:

$$a_1 \ X^2 + a_2 \ XY + a_3 \ XZ = XT \quad (2)$$
$$a_1 \ XY + a_2 \ Y^2 + a_3 \ YZ = YT \quad (3)$$
$$a_1 \ XZ + a_2 \ VZ + a_3 \ Z^2 = ZT \quad (4)$$

The summation ( ) is carried out for p elements

where p = l (m) n (5)
l = number of years analyzed;
m = number of outflow rates chosen;
n = number of storage levels chosen.

The solution to the system of three simultaneous equations is given by finding the values of a_1, a_2, a_3 in the following matrix representation of the normal equations:

$$\begin{vmatrix} X^2 & XY & XZ \\ XY & Y^2 & YZ \\ XZ & YZ & Z^2 \end{vmatrix} \cdot \begin{vmatrix} a_1 \\ a_2 \\ a_3 \end{vmatrix} = \begin{vmatrix} XT \\ YT \\ ZT \end{vmatrix} \quad (6)$$

Either Gaussian elimination or matrix inversion can be used to solve by a_1, a_2, a_3 (Carnahan et al., 1969).

Having determined the regression coefficients, it is now possible to solve directly for any one of the original variables given the other two. In particular, we wish to produce the volume-outflow curves for specific storage levels. This requirement can be satisfied by fixing the storage level, incrementing through a range of seasonal volumes, and solving for outflow settings at each step using Newton's iteration method. (Carnahan et al., 1969)

A necessary step in obtaining the volume-outflow curve equation is a three-dimensional matrix of seasonal volumes, storage, and outflow rates. These values are derived from the storage-outflow relationships for individual years (fig. 4). To fit a curve objectively to the storage-outflow date pairs and expedite processing, a fifth degree least squares polynomial regression procedure is used. It takes the form:

$$S = b_1O + b_2O_2 + b_3O_3 + b_4O_4 + b_5O_5 + b_6 \quad (7)$$

where b_1, b_2, b_3, b_4, b_5, b_6 are regression coefficients, and S and O are as previously defined. The coefficient of determination for equations fitted by polynomial regression is extremely good, generally in the range of 0.990 to 0.999.

Having explicitly defined the regression equations, a Newton iteration technique was used to find outflow at previously selected storage volumes for each year. This yields the required three-dimensional matrix of data elements that is input to the volume-outflow curve algorithm.

The volume-outflow curve algorithm has been subjected to verification tests to insure its mathematical integrity. In addition, validation analyses have been conducted with actual data from various locations throughout the West. Comparisons have shown that the results obtained from using the volume-outflow curve algorithm are identical to manual procedures.

RSVP Computer Program

To facilitate SCS field personnel's ability to use this procedure, a Reservoir Storage Volume Planning (RSVP) computer program was written. The program was designed to integrate data entry, streamflow screening, flow analysis, curve fitting, plotting, and error analysis. RSVP runs on a Data General MV 8000 minicomputer with graphical output directed to Tektronix 4100 or 4200 series color terminals. It will also produce Hewlett Packard 7475A Plotter output.

The RSVP program is available on CFS. This system is a menu-driven set of programs that supports Soil Conservation Service activities. It also contains many programs valuable to Soil Conservation activities as well as data to support those activities. Information on CFS can be obtained by contacting the West National Technical Center.

RSVP currently includes 11 modules. Eight of these modules are normally executed sequentially to produce a set of volume-outflow curves. However, certain modules may be executed out of sequence. The modules in the RSVP program are:

1. Data Input
2. Hydrograph Plotting
3. Reservoir Inflow Correction
4. Flow Analysis
5. Storage vs. Outflow
6. Volume-Outflow Curve Development
7. Volume-Outflow Error Analysis
8. Graphics of Volume-Outflow Curve
9. HP Plotter Output or Retrieval
10. Display TABLE file by year
11. REServoir Management Evaluation Program (RESMEP)

Table 1 summarizes input and output requirements and file naming conventions for each module. A brief description of the function of each of these routines is given, along with selected output examples.

Data Input

This module provides for entry of mean daily flow data into a file from either keyboard or from a WATSTORE[1] daily values file. Space is allocated for storage of up to 40 full years of data; partial year data, e.g., April-July, are also permissible. The input file created is available for use in the Hydrograph Plotting, Reservoir Correction, and Flow Analysis modules.

1 WATSTORE—an acronymn for the U.S. Geological Survey's computerized WATer STORage and information retrieval system.

Hydrograph Plotting

Daily hydrograph plots are produced onscreen, and a file is prepared for plotter output. An average hydrograph for all or part of a year is calculated based on the input data set. Seven hydrographs may be displayed on the same graph. Figure 6 shows a hydrograph for Mackay Reservoir in Idaho for water year 1984.

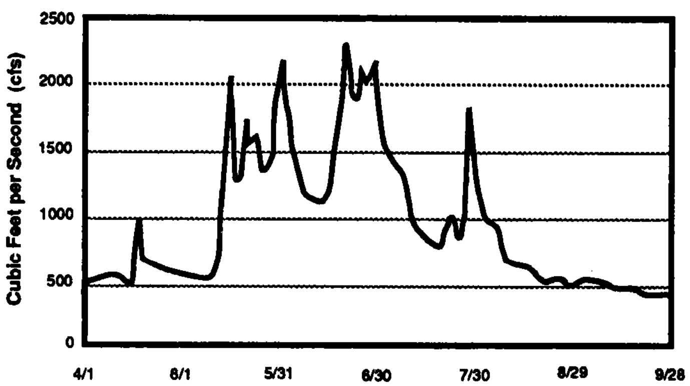


Figure 6. Discharge 1984.

Figure 7 is an example of a storage outflow curve for Mackay Reservoir in Idaho for one year. The storage volumes are held constant for all years to establish a uniform data set for subsequent analyses. A file of storage and outflow is generated and passed to the Volume-Outflow Curve Equation module.

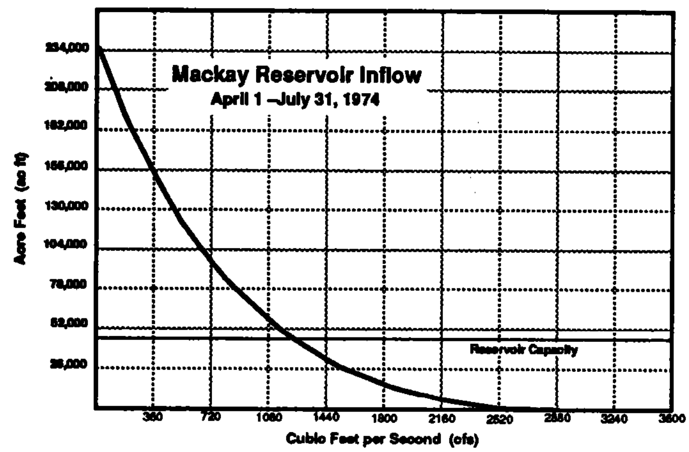


Figure 7.—Computer-generated storage-outflow curve.

Flow Analysis

In this module, the amount of storage that would occur at various outflows is calculated for a seasonal flow period, e.g., April-July for each year. A file containing paired values of outflow and storage for each year is generated and this file is passed to the Storage vs. Outflow module.

Storage vs. Outflow

The storage-outflow data file created in the Flow Analysis module is read in this routine and a fifth degree polynomial expression fitted to the paired data points for each year. The resultant equation relates storage volume to outflow for each year.

Volume-Outflow Curve Equation

A multiple regression analysis is performed on the entire three-dimensional data set which consists of storage, forecasted outflow and seasonal volume per the Volume-Outflow Curve algorithm. This step of the analysis includes the data for all of the years. A single equation is produced which is used to generate volume-outflow curves for 21 storage levels. Figure 8 is a copy of the April-July Volume-Outflow curve equation for Mackay Reservoir in Idaho based on 20 years data. Figure 9 shows an example of a single volume-outflow curve for the 32,000 acre-foot to store level for Mackay Reservoir based on this equation. The two-digit numbers indicate observed data points in the corresponding year. The regression equation is saved for later use in the Volume-Outflow Curve Error Analysis and Volume-Outflow Curve Plotting modules.

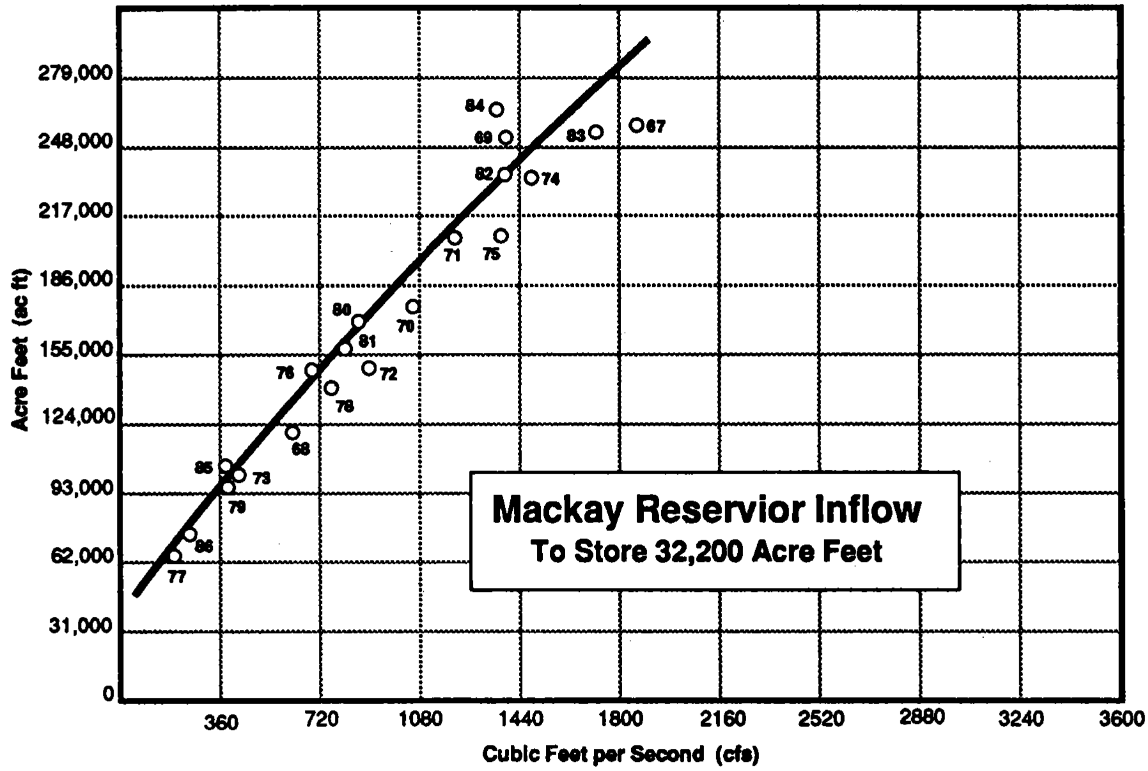


Figure 8.—April-June inflow to Mackay Reservoir (volume-outflow curve equation).

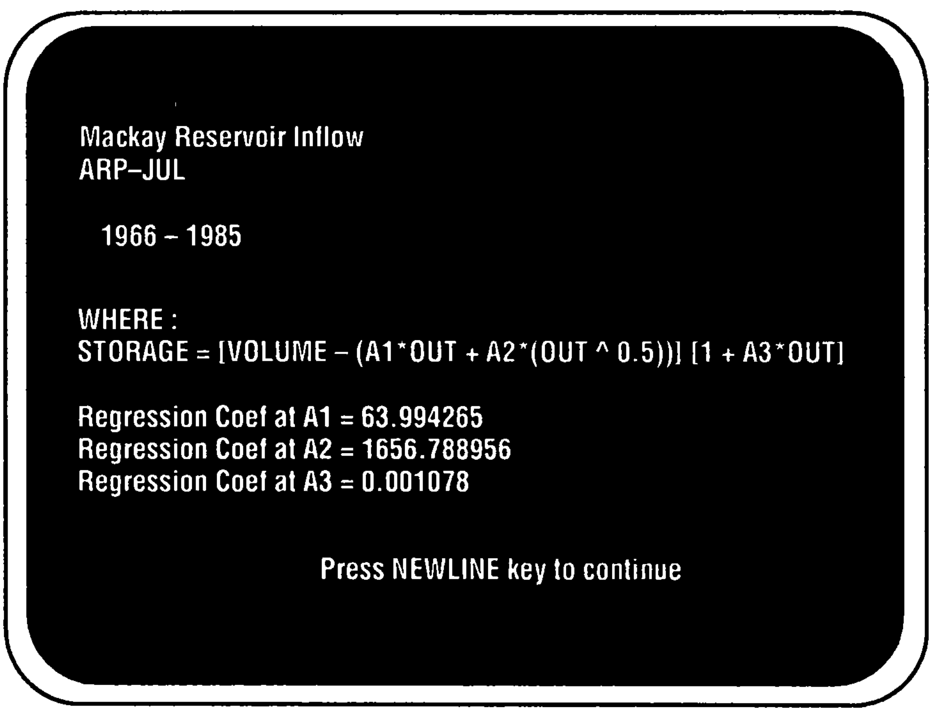


Figure 9.—To store 32,000 acre-feet, April-July inflow to Mackay Reservoir 1966-85.

Volume-Outflow Curve Error Analysis

This module analyzes the degree to which the volume-outflow curves fit observed data. Residual errors for each volume-outflow curve are calculated and plotted (figure 10). In addition, a composite error analysis is generated for all 21 storage levels. The mean error and standard error of the estimate for the linear regression relationship are calculated and printed (fig. 11).

Volume-Outflow Curve Plotting

This module permits a user to select up to 10 different operating volume-outflow curves for display on a single graph. Figure 12 shows a family of volume-outflow curves for Mackay Reservoir that exemplifies the output format. Observed data points are eliminated from the plot in order to produce a chart suitable for inclusion in a reservoir operating plan report.

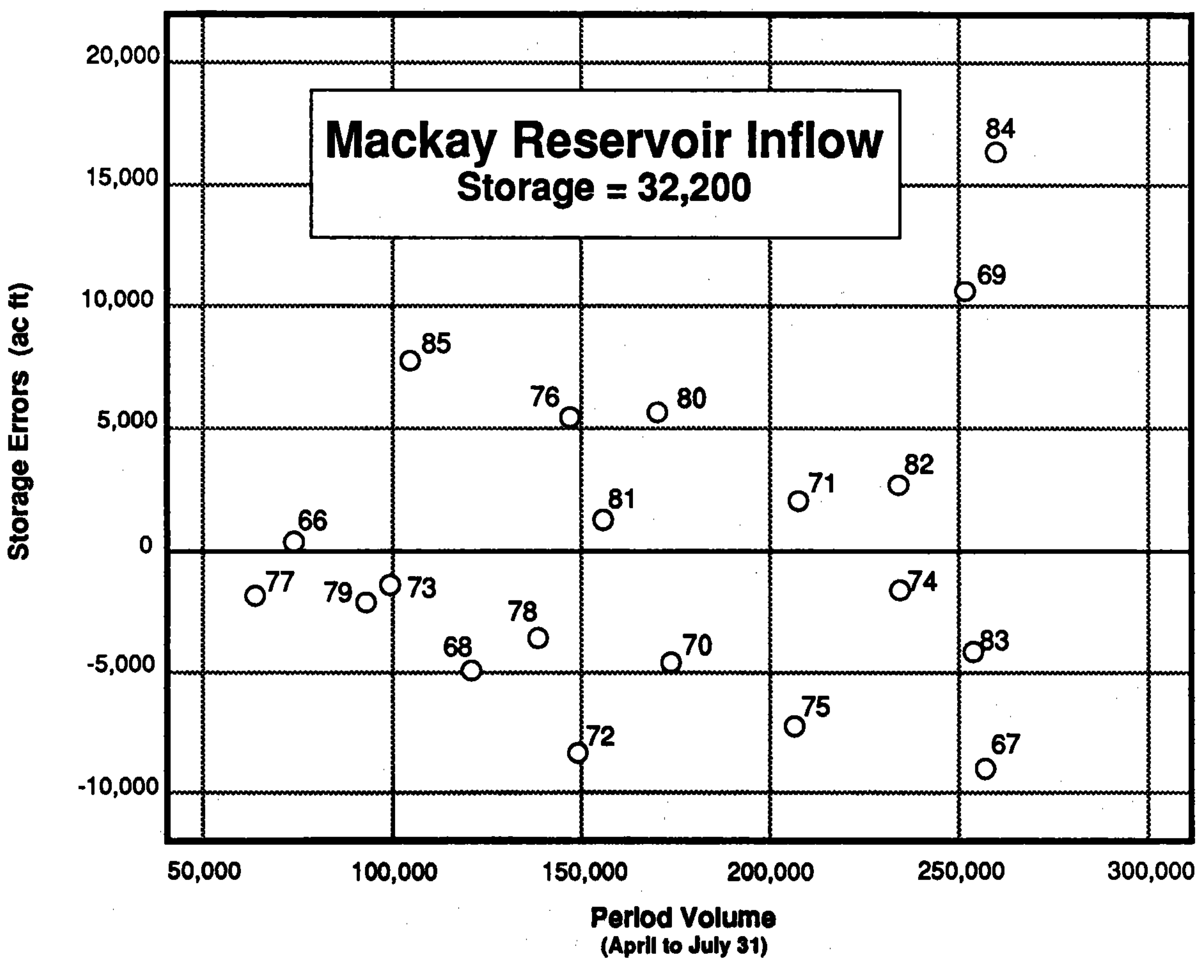


Figure 10.—Error analysis.

Summary Statistics for Error:

N	420
MEAN	-55.7
RMSE	7707.1

Freq Table for Error:

>=	>	
-30000.0	-20000.0	3
-20000.0	-10000.0	28
-10000.0	0.0	205
0.0	10000.0	143
10000.0	20000.0	35
20000.0	30000.0	6

Press RETURN to Continue.

Figure 11.—Mackay Reservoir error summary—April-July inflow.

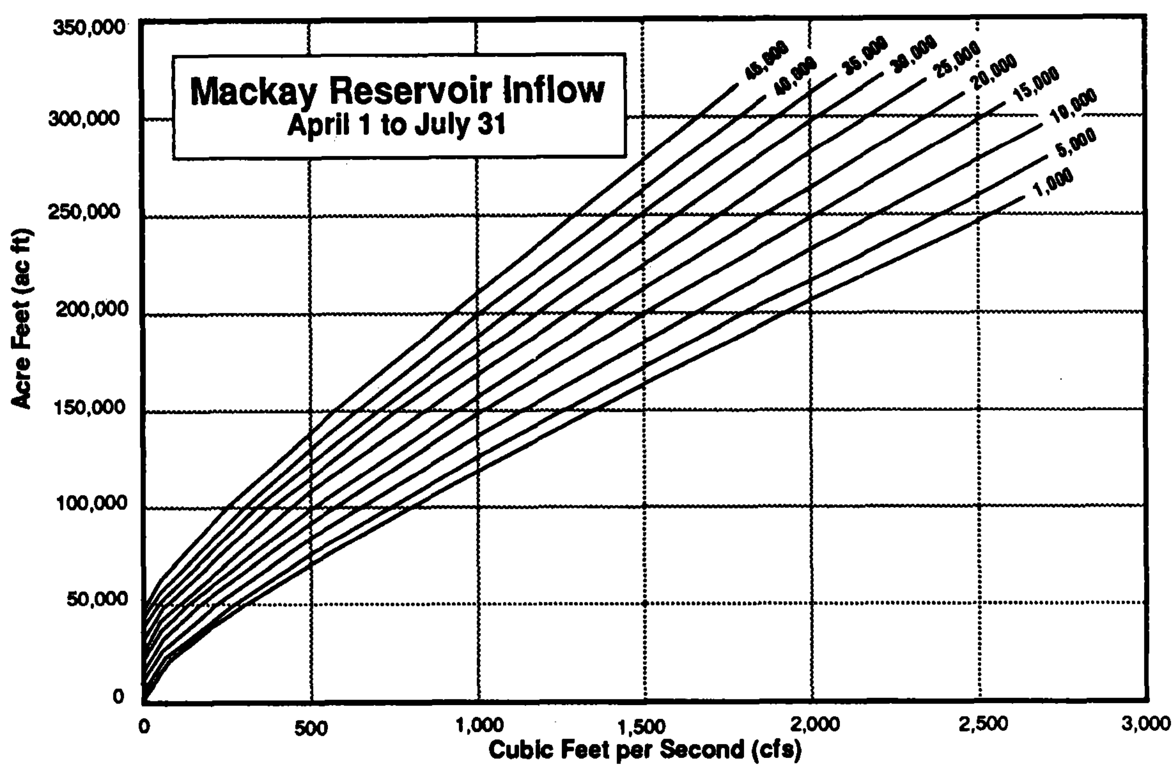


Figure 12.—Volume-outflow curves, April-July inflow to Mackay Reservoir, 1966-1985

Volume-Outflow Curve Application

It is instructive to go through an abbreviated example of developing and applying the results of the volume-outflow curve access computer program. Mackay Reservoir is used to show how volume-outflow curves are generated and how they guide the management decision process. This reservoir is managed primarily for irrigation and recreation, but potential impacts on other interests affect how the project is operated.

Mackay Reservoir is in the Big Lost River watershed. It has a drainage area of 813 square miles. The streamflow regime is dominated by snowmelt runoff. Reservoir capacity is 44,370 acre-feet. Daily inflow records are available for the 20-year period from 1966 to 1985. Considerable downstream damage occurs at flows in excess of 1500 cfs. A minimum outflow of 50 cfs is required to support downstream fish populations. Streamflow forecasts are issued for reservoir inflow monthly January through June for the main runoff period.

Daily streamflow data were entered from the keyboard using the RSVP Data Input module. The Hydrograph Plotting module was invoked to produce hydrograph plots, including the average hydrograph shown in figure 13. The Flow Analysis, Storage vs. Outflow, and volume-outflow Curve Equation modules were next executed sequentially to create the following Volume-Outflow curve regression equation for the April-July period.

$$S = [V - 63.99(O) - 1657 (O)^{0.5}] / (1 + .0011(O)) \quad (8)$$

This equation produced the following composite error statistics when run through the Error Analysis module:

Mean Error = -56 acre-feet
Standard Error of Estimate = 7707 acre-feet

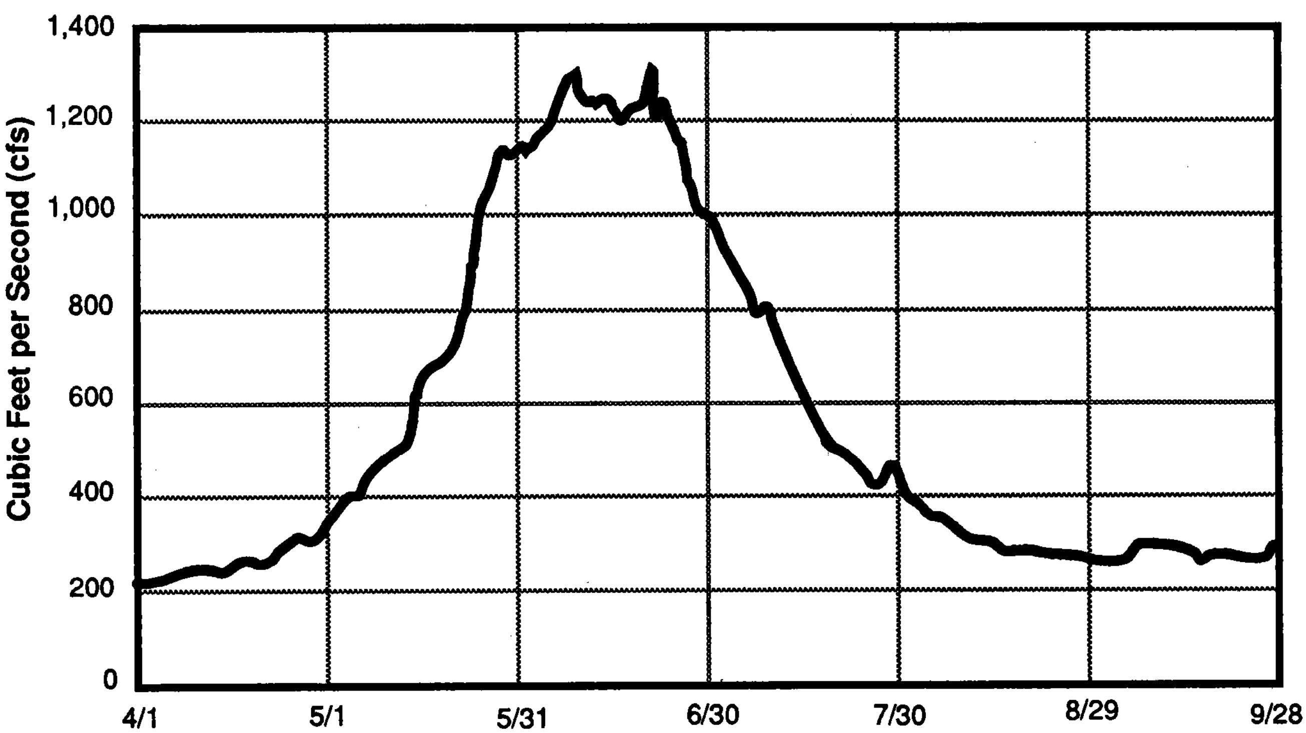


Figure 13. Average hydrograph for inflow to Mackay Reservoir, 1966-85.

Finally, the volume-outflow curves shown in figure 14 were generated using the Volume-Outflow Curve Plotting module. A similar procedure was followed to produce the May-July volume-outflow curves shown in figure 15. These two charts used in conjunction with streamflow forecasts provide the means to make outflow adjustments commensurate with anticipated runoff. Illustrations of how the volume-outflow curves might be used in a high snowpack year and a low snowpack year are given for comparison.

Low Runoff Year

On March 1, assume that the reservoir has 4,370 acre-feet of water in storage and the most probable (MP) April-July inflow forecast is 206,000 acre-feet, or 76 percent of average. Average April-July inflow is 259,000 acre-feet. The reasonable minimum forecast (RMN) is 163,000 acre-feet; the reasonable maximum forecast (RMX) is 257,000 acre-feet. Subtracting current storage from the reservoir's capacity leaves 40,000 acre-feet required to fill the reservoir. Entering the April-July operating curves of figure 14 with RMN, MP, and RMX and moving horizontally to the 40,000 acre-feet to store curve yields release rates of 700, 1,100 and 1,400 respectively. Based on these figures, a logical decision would be to store as much water as possible and to release outflow of only 700 cfs.

By April 1, reservoir storage was increased by 5,000 acre-feet, thus requiring 35,000 acre-feet to fill the reservoir. The April-July forecast has been raised slightly to 170,000 acre-feet for RMN, 210,000 for MP, and 260,000 for RMX. Entering the April-July volume-outflow curves with these values indicates outflow settings of 800, 1,150, and 1,500 cfs, respectively. Both outflow settings found with RMN and MP inflows are well above the minimum desirable outflow of 450 cfs necessary to satisfy downstream water rights. Volume-outflow procedure would assume that the operator would pass inflow until the selected outflow is reached. In low years, the decision could be made to store as much as possible until May 1 forecasts are received.

During April, runoff was sufficient to provide an additional 5,000 acre-feet of storage, leaving 30,000 acre-feet necessary to fill the reservoir. The May-July MP has been raised to 80 percent of normal, or 199,000 acre-feet. The May-July average is 249,000 acre-feet. RMN is 166,000 acre-feet, and RMX is 231,000 acre-feet. Using May-July volume-outflow curves of figure 15, the outflows for RMN, MP, and RMX would be 1,100, 1,300, and 1,600+ cfs, respectively. Again volume-outflow would assume inflow and outflow until the outflow index is exceeded. The decision would probably be made to maintain releases at the minimum levels and continue storing as much water as possible until irrigation demands exceed inflow. With the expected low runoff, the probability of generating channel-damaging flows in excess of 1,500 cfs is minimal. In such a low runoff year, when reservoir storage is low, demand for irrigation water will be greater than the outflow rates that would permit filling the reservoir. Water users must then decide whether they would rather use the water for irrigation or put it into storage for later delivery when crop consumptive demands are the highest.

High Runoff Year

On March 1, assume that 40,000 acre-feet are needed to fill the reservoir and the April-July MP is 328,000 acre-feet or 121 percent of average. RMN and RMX are predicted to be 280,000 and 374,000, respectively. Entering figure 14 with these predictions yields outflows of 1,700, 2,000, and 2,500 cfs. These outflow rates are in the range that raises concern about the possibility of being forced into releases higher than are desirable later in the season.

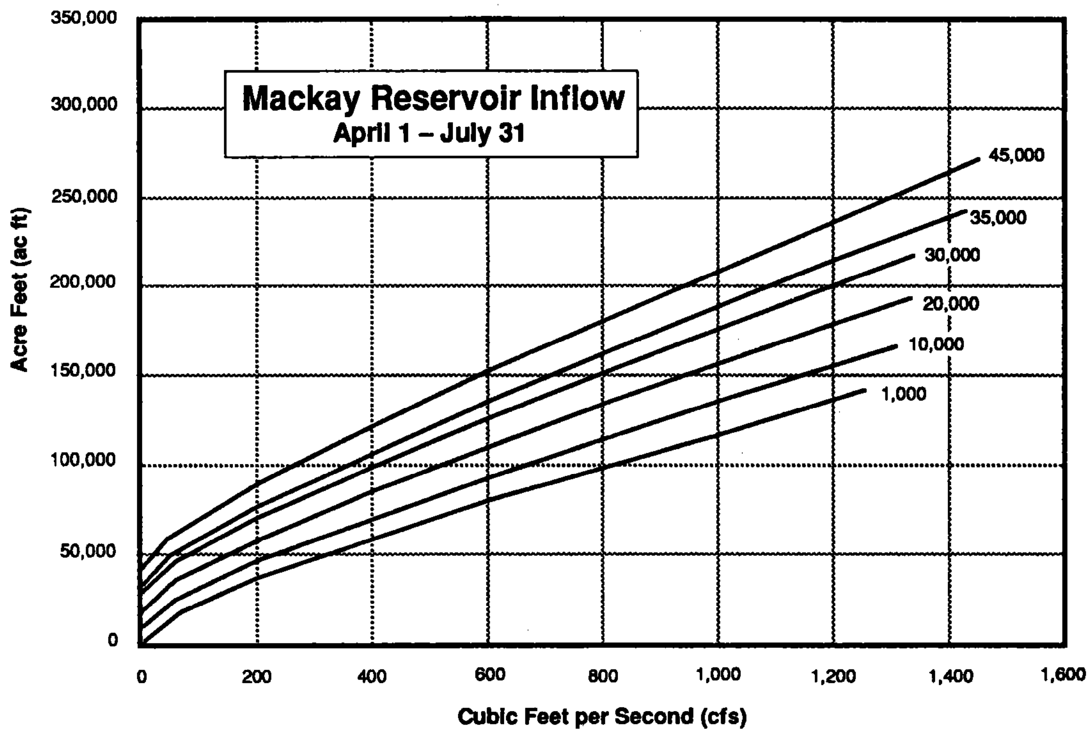


Figure 14—Volume-outflow curves—April-July inflow to Mackay Reservoir, 1966-85.

They also support the contention that there is likely to be plenty of water to fill the reservoir and satisfy all downstream requirements. The decision will probably be made to set outflow equal to maximum safe discharge of 1,500 cfs and wait until the April 1 forecasts are received.

When April 1 comes, reservoir storage has dropped to a level requiring 43,000 acre-feet of water to fill. Streamflow projections of April-July runoff are for RMN, MP, and RMX values of 294,000, 328,000, and 369,000 acre-feet, respectively. Entering figure 14 with these numbers translates into potential release rates of 1,600, 1,900 and 2,200 cfs corresponding to RMN, MP, and RMX. The decision would be made to set outflow rates at maximum 1,500 cfs. Any significant increase in storage could create a potentially hazardous situation if abnormally high precipitation and temperatures occur in the next several months.

On May 1, the MP is for a May-July flow of 130 percent of average, or 324,000 acre-feet. RMN and RMX are for flows of 295,000 and 350,000 acre-feet, respectively. Reservoir storage has been maintained, and 43,000 acre-feet of storage is available. Using these figures in the May-July volume-outflow curves (figure 15) gives release rates ranging from 1,600 cfs for RMN to 2,100 cfs for RMX with an intermediate value of 1,900 cfs for MP. These numbers continue to indicate a heavy runoff and a high probability that release rates will have to approach or exceed 1,500 cfs, the threshold at which damage occurs at downstream reaches in the channel. The decision would be made to set outflow rates about 1,500 cfs and continue to monitor weather conditions during the month for unusually warm conditions or heavy precipitation. In any case, the flows below Mackay Reservoir will probably exceed 1,500 cfs.

Rule Curves

The earlier sections of this document described the technical processes that result in the volume-outflow curves. The technical analysis assumes that (1) inflow matches outflow until the inflow is equal to or greater than the outflow index value of the volume-outflow curve, (2) the structure can handle the outflow at any storage level, and (3) available storage can only

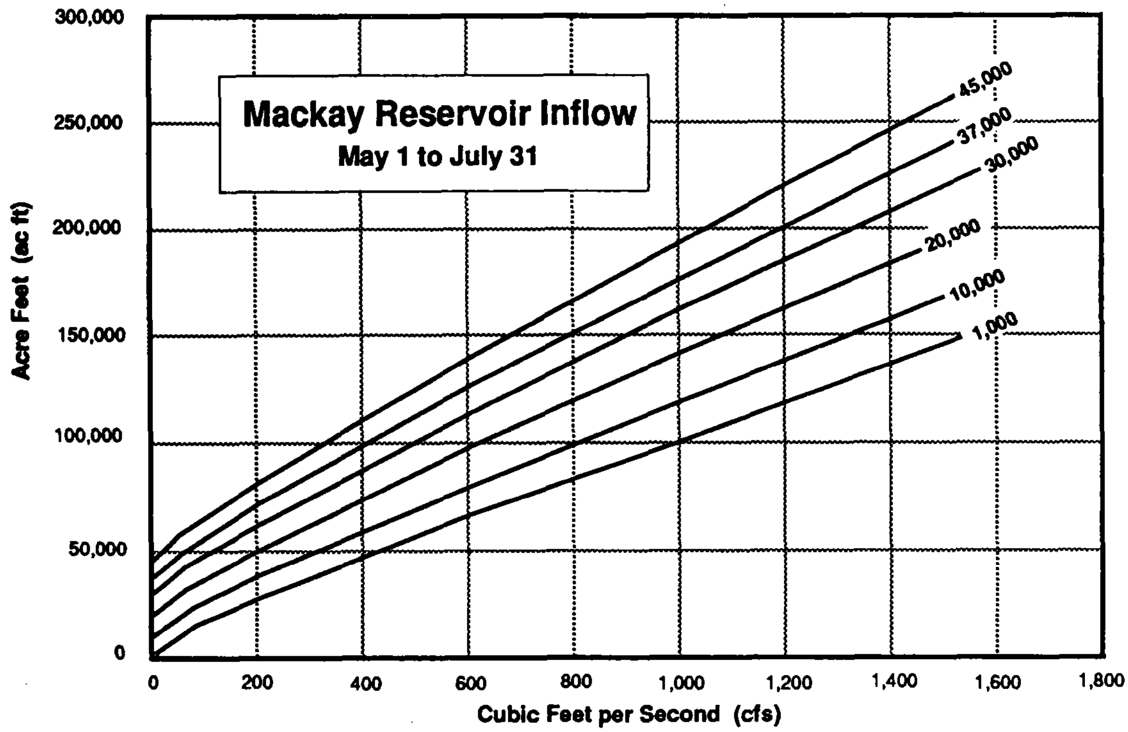


Figure 15.—Volume-outflow curve—May-July inflow to Mackay Reservoir, 1966-85.

decrease. The technical analysis uses least squares to determine representative curves for a particular structure. This statistical technique is very accurate at and within one standard deviation of the mean, but the technique fits extreme occurrences very poorly. Managing the extremes in water supply is the most important challenge to be met in operating a reservoir for water supply or flood protection. To be successful, the reservoir operator must be able to handle the extremes while addressing other goals that may be important to operation of the structure. One example of this is a structure that is used as a source of irrigation water and is a valuable recreational resource to the local community. Both of these functions, irrigation water supply and recreation, are valuable, but they may be incompatible during drought or flood conditions.

This section will outline how data are gathered and how the data are processed into a rule curve that can be used to manage a reservoir under extreme conditions and accomplish goals established for that structure.

DATA REQUIREMENTS

This procedure addresses three reservoir operation situations which are defined in order of their importance to reservoir operations. The worst case is one in which the only information available is reservoir outflow and storage. To be able to reconstruct outflow under this "situation" the manager evaluates the daily reservoir contents by subtracting the previous day's contents from the current contents and multipling by 0.50417, the factor for conversion from acre-feet to cubic feet per second (cfs). The result is the change in storage expressed in mean daily cfs. The change in storage is then algebraically added to the outflow record available for the reservoir. The outflow record is usually at a downstream point. A gaging point several miles downstream can be used if there is no inflow, other than minimal local contribution, between the gaging point and the reservoir. This reconstruction does not precisely represent the actual inflow to the reservoir, but the errors are normally small enough to be inconsequential. Care must be taken when applying RSVP in judging the adequacy of the record because of the potential for large errors due to significant evaporative loses. Another source of error might be significant bank storage. These data are then smoothed, primarily to remove nonsensical values that occur because of errors in the measurement of reservoir contents and mean daily outflow. The estimation of the reservoir inflow is then ready for RSVP processing.

The next situation is one in which part of the inflow is measured, and part is not. An estimate of the unmeasured data can be obtained if information is available for the contents of the reservoir on a daily basis, and if the outflow from the reservoir is available. This is a more involved process but it will provide a much more precise estimate of the actual inflow to the reservoir. The first step is to provide an estimation of the total inflow to the reservoir. This is done by processing the data precisely in the same manner as the worst case scenario; the inflow is estimated from the reservoir contents and outflow record and then smoothed. The actual measured portion of the inflow is algebraically subtracted from the estimated inflow. The remaining value is the estimate of the unmeasured inflow. This inflow value can be graphed and those data values obviously in error can be corrected. If this inflow represents a significant portion of the actual inflow, and substantial errors seem to be associated with the estimate, the hydrologist may need to investigate alternate methods of estimating the unmeasured portion. One alternate technique is to calibrate the measured portion using one of the available watershed simulation models and then estimate the unmeasured portion using the parameter estimations from that calibration. This technique, should produce more precise results than using only the contents and outflow values. Again, the primary goal is to achieve a good estimate of the inflow value to be used in the RSVP process.

In the final situation, the inflow to the reservoir is known. This scenario provides data that can be directly input to the RSVP process. Interesting observations were made during investigations on available data: in the Eastern United States the inflow or at least the primary inflow to a reservoir is usually measured, but reservoir content, which is important from a water supply standpoint, is seldom measured. In the Western United States the inflow is not normally measured, but outflow and reservoir contents are measured because they are important to water supply management. In both cases, the water resource is inadequately measured, providing serious challenges to the hydrologist.

In any case the ultimate result is only as good as the inflow data used in the analysis. The best estimate of the inflow data will then provide the best evaluation for operation of the reservoir. Tables 2 and 3 show the input data format, WATSTORE card format, and the resulting output format, CFS table format, of the "INPUT" and "RESERVOIR CORRECTION" portions of the CFS RSVP system respectively.

DATA SOURCES

The data for the inflow can be obtained from a number of sources. The easiest source for the data is the U.S. Geological Survey (USGS) WATSTORE system, which is a database maintained by the USGS in Reston, Virginia. National Technical Centers maintain an access agreement with the USGS for retrieval and analysis of Water Resource data gathered by the USGS. The RSVP software includes a program under "INPUT" that directly interprets the WATSTORE data files retrieved and places those data files into an RSVP compatible format. Reservoir Data is also available from the USGS.

Recently Earth Info Systems, formerly U.S. West Publications Incorporated, has provided the same USGS data in many formats on CD-ROM. Only the most recent data must be retrieved from the WATSTORE system in Reston. If the site is not measured by the USGS, the information must be obtained from the reservoir operator. In many cases, the operator will have kept inadequate information on operation of the structure, and developing a reservoir guide begins by working with the operator to obtain good measurements.

The data need not be for consecutive years. For example, if adequate records were kept for 1967, 1969, 1975, 1977, 1978, 1980, 1982, 1983, 1987, and 1988, then a preliminary analysis can be executed on that data and continued efforts made to improve data collection. As stated before, minimum of 10 years' data are required. In addition, those 10 years should include a reasonable sample of high, low, and average years. If adequate data have been collected, they can be made available to the RSVP software through direct data input provided in the "INPUT" section of RSVP, or they can be read from other computer input and Mreformated to a compatible format. In any case, it will be helpful to work with an NTC hydrologist to make the data available to RSVP.

RSVP PROCESSING

At this point in the process, the data necessary to complete the RSVP analysis are complete, and the analyst has only to step through the system to produce the storage-outflow curve, the volume-outflow curves and the combined volume-outflow figure for use in the evaluation of reservoir operations. These evaluations provide the hydrologist with the information necessary to develop the reservoir "rule curves" that provide guidance for the operator to achieve operational goals. The previous descriptions of the technical processes provide adequate information for development to the final volume-outflow figures. The following section describes the development of the "rule curve."

"RULE CURVE" DEVELOPMENT

Rule curves are the actual time versus contents curve that give the operator the target contents necessary to control the contents of the reservoir given the runoff expected. Figure 16 is a representative rule curve for MacKay Reservoir in Central Idaho.

These rule curves are developed by reviewing the actual operational results of the volume-outflow figure developed in the RSVP system. The Water Supply Forecasting Staff (WSFS) has developed a program, Reservoir Management Evaluation Program (RESMEP), that allows analysis of the entire period of record given a set of trial rule curves.

TABLE 1

MODULE 1	MODULE 2	MODULE 3	MODULE 4	MODULE 5	MODULE 6	MODULE 7	MODULE 8
DATA INPUT	HYDROGRAPH PLOTTING	RESERVOIR CORRECTION	FLOW ANALYSIS	STORAGE VS DISCHARGE	RULE CURVE EQUATION	RULE CURVE ERROR	RULE CURVE PLOTTING
PROMPTS	PROMPTS	PROMPTS	PROMPTS	PROMPTS	PROMPTS	PROMPTS	PROMPTS
KEYBOARD and/or WATSTORE format ASCII file	Any .DIS or CON. file (from 1 or 3)	.DIS or CON. file (from 1)	.DIS file (from 1 or 3)	flow."period" file	stor.dis."period" file	rule."period" rulecurve."period" coeffile."period"	
LOCAL	LOCAL	LOCAL	LOCAL	LOCAL	LOCAL	LOCAL	LOCAL
I/O	I/O and GRAPHICS	I/O	I/O	I/O and GRAPHICS	I/O and GRAPHICS	GRAPHICS	I/O and GRAPHICS
file.DIS	graphicfile.TEK	file.DIS	flow."period"	stor.dis."period"	rule."period"		

```
2 13127000                  0006000003                  ENT
3 13127000        19861001  58.00  80.00 145.00 151.00 154.00 157.00 160.00 165.00
3 13127000        19861002 168.00 170.00 172.00 175.00 175.00 107.00  57.00  56.00
3 13127000        19861003  66.00  79.00  80.00  81.00  84.00  83.00  78.00  75.00
3 13127000        19861004  75.00  76.00  76.00  78.00  78.00  79.00  79.00
3 13127000        19861101  81.00  81.00  82.00  83.00  85.00  86.00  87.00  87.00
3 13127000        19861102  88.00  88.00  91.00  92.00  93.00  93.00  95.00  95.00
3 13127000        19861103  96.00  96.00  97.00  97.00  99.00  99.00 100.00 102.00
3 13127000        19861104 104.00 105.00 106.00 106.00 107.00 108.00
3 13127000        19861201 110.00 114.00 115.00 115.00 115.00 117.00 119.00 118.00
3 13127000        19861202 119.00 119.00 120.00 121.00 121.00 121.00 121.00 121.00
3 13127000        19861203 120.00 119.00 119.00 119.00 119.00 119.00 119.00 119.00
3 13127000        19861204 119.00 119.00 119.00 119.00 119.00 119.00 119.00
3 13127000        19870101 119.00 119.00 119.00 119.00 119.00 119.00 121.00 121.00
3 13127000        19870102 121.00 121.00 121.00 121.00 121.00 121.00 121.00 121.00
3 13127000        19870103 121.00 121.00 121.00 121.00 121.00 119.00 119.00 119.00
3 13127000        19870104 119.00 119.00 119.00 119.00 120.00 120.00 120.00
3 13127000        19870201 120.00 120.00 120.00 121.00 120.00 120.00 120.00 120.00
3 13127000        19870202 120.00 119.00 119.00 120.00 119.00 120.00 120.00 120.00
3 13127000        19870203 120.00 120.00 120.00 120.00 120.00 120.00 119.00 119.00
3 13127000        19870204 118.00 119.00 120.00 121.00
3 13127000        19870301 122.00 122.00 123.00 123.00 124.00 124.00 124.00 124.00
<<       >>
<<       >>
3 13127000        19870403 117.00 116.00 115.00 115.00 116.00 118.00 117.00 117.00
3 13127000        19870404 115.00 115.00 115.00 115.00 115.00 115.00
3 13127000        19870501 232.00 353.00 356.00 353.00 344.00 435.00 532.00 523.00
3 13127000        19870502 521.00 516.00 509.00 526.00 554.00 564.00 572.00 573.00
3 13127000        19870503 535.00 413.00 295.00 211.00 176.00 190.00 268.00 343.00
3 13127000        19870504 446.00 670.00 663.00 490.00 420.00 396.00 476.00
3 13127000        19870601 491.00 518.00 516.00 586.00 637.00 699.00 732.00 694.00
3 13127000        19870602 641.00 541.00 435.00 378.00 356.00 358.00 385.00 443.00
3 13127000        19870603 491.00 535.00 546.00 528.00 512.00 492.00 481.00 482.00
3 13127000        19870604 476.00 472.00 468.00 481.00 490.00 480.00
3 13127000        19870701 487.00 507.00 492.00 472.00 460.00 485.00 511.00 553.00
3 13127000        19870702 581.00 596.00 655.00 653.00 641.00 638.00 622.00 652.00
3 13127000        19870703 642.00 441.00 217.00 183.00 182.00 164.00 146.00 145.00
3 13127000        19870704 204.00 241.00 345.00 549.00 623.00 638.00 648.00
3 13127000        19870801 631.00 635.00 660.00 663.00 706.00 721.00 725.00 719.00
3 13127000        19870802 672.00 650.00 702.00 728.00 676.00 615.00 572.00 554.00
3 13127000        19870803 490.00 415.00 384.00 365.00 328.00 285.00 267.00 275.00
3 13127000        19870804 272.00 258.00 232.00 201.00 191.00 189.00 192.00
3 13127000        19870901 213.00 225.00 221.00 217.00 214.00 210.00 219.00 225.00
3 13127000        19870902 236.00 259.00 252.00 243.00 246.00 244.00 243.00 237.00
3 13127000        19870903 225.00 213.00 205.00 204.00 205.00 197.00 188.00 191.00
3 13127000        19870904 194.00 198.00 200.00 193.00 185.00 184.00
```

Table 2.—WATSTORE card format

Station :13127000, BIG LOST RIVER below MacKay Reservoir

Day	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1	895	1153	225	262	142	224	333	457	2687	818	368	250
2	276	344	225	212	193	173	333	454	2917	771	343	243
3	314	317	175	212	197	224	282	513	2817	727	357	282
4	288	327	225	212	171	224	283	764	2998	726	314	255
5	323	300	225	212	222	173	335	685	3017	632	354	250
6	331	290	225	212	171	224	284	749	2645	592	329	244
7	335	290	175	212	222	274	336	730	2284	573	303	240
8	338	292	225	212	171	274	338	668	1995	507	356	282
9	329	286	175	212	222	224	338	575	1729	522	295	279
10	331	272	175	212	171	274	333	658	1495	514	274	258
11	333	259	78	161	222	224	363	551	1459	498	299	257
12	334	245	96	212	222	224	411	533	1585	504	278	263
13	322	248	147	210	121	274	361	440	1685	452	252	252
14	324	244	351	209	222	274	387	462	1706	452	233	287
15	266	242	402	156	224	224	352	461	1807	442	264	322
16	185	239	251	207	173	224	403	463	1727	470	200	316
17	44	252	251	207	224	274	356	415	1668	394	233	320
18	68	277	201	207	174	224	305	467	1728	384	268	310
19	1232	223	252	205	224	224	304	440	1717	429	255	322
20	304	226	203	152	171	274	302	557	1476	445	239	315
21	166	224	202	202	222	225	351	805	1244	370	332	324
22	201	225	207	150	173	227	401	844	1912	446	267	315
23	283	220	258	201	173	277	553	836	426	418	306	306
24	241	221	207	200	225	227	606	729	1057	443	250	295
25	292	275	208	149	226	277	615	772	1064	448	331	275
26	314	223	206	198	175	227	503	873	1017	466	260	217
27	321	224	206	198	227	279	587	1394	1087	410	290	271
28	314	174	255	147	174	229	538	1967	1007	426	264	289
29	322	225	208	196	–	279	516	2224	78	370	295	257
30	240	224	258	144	–	330	446	2494	917	423	279	450
31	47	–	205	194	–	230	–	2584	–	344	264	–
AF.	19662	16980	13293	12050	10818	14945	23514	526891	101060	30577	17755	16950
max.	1232	1153	402	262	227	330	615	2584	3017	818	368	450
tot.	9913	8561	6702	6075	5454	7535	11855	26564	50951	15416	8952	8546

—AF,TOT Expressed in CFS days—

Table 3—CFS Table Format (USGS publication format)