Reservoir Operations Guides - Application on Three Reservoirs

by

James K. Marron 1/, Phillip E. Farnes 2/, and Christian J. Pacheco 3/

INTRODUCTION

Over the past 82 years, water resources in the Western United States have been developed to a level unparalleled in history. Men have become wealthy in both the development of water resources as well as growing crops and raising livestock. The Cadillac Desert, a book by Marc Reisner, describes water development and its results. The West has been a thriving success due primarily to these water projects. With that success has come two very important facts. First, the water resources that were available for development have for the most part been completed. Secondly, the water resources that have been developed are stretched to their limits due to increasing demands from a growing population. In 1906 Dr. J. E. Church began the use of a technique that provided forecasts of available water. The forecast of the rise in Lake Tahoe, which represented the volume of water available, was the first water supply forecast in the West. This forecast was also intended to keep shoreline residents and recreational users safe from excessively high water levels. This was the beginning of the use of technical information to increase the efficiency of water usage. Not coincidentally, this application coincided with the development of the first Bureau of Reclamation project in the West, to develop the Lahontan Irrigation Project using water from the Carson and Truckee Rivers. In 1906 the Truckee River Basin water users were provided information to manage the basin's water resources. Now we are thrown full force into the requirement for improved efficiency in the use and management of our hard earned water. The logical result is that water resources must be used more efficiently and with more concern for the quality of the water after its use.

Obviously, most manageable water resources are directly associated with reservoirs. We have dotted the landscape with dams so that we can manage the flow of many of the rivers in the West. These reservoirs range from one acre-foot to millions of acre-feet. Many are not forecast and the fill and spill technique is the only type of management used. The two forecasting agencies, the National Weather Service and Soil Conservation Service, provide forecast information on approximately 606 reservoirs and manageable lakes. Of these, approximately 95% are either "managed" using the technique of fill and spill or using only flood management curves provided by the agency designing the structure.

The fill and spill technique is one in which the manager fills the structure as soon as possible. This technique usually achieves a full reservoir but the reservoir is full before the peak runoff occurs. This often resulting in severe streambank damage and erosion as well as damage to wildlife resources and sometimes the reservoir structure itself. The flood management curves provided for many structures are extremely valuable in reducing the impact of flooding and insuring the integrity of the structure itself but may have little value in achieving a full reservoir in water-short years or maintaining discharges adequate for irrigation, municipal, and industrial uses after high flows have passed.

RESERVOIR STORAGE VOLUME PLANNING TECHNIQUE

The Soil Conservation Service has developed and released a technique to help water users manage reservoirs (Shafer et al., 1986). The reservoir management technique reviewed here bases management decisions on water supply forecasts, and is being applied to several reservoirs in the West. The three reservoirs selected for review in this paper demonstrate the application of this technique to achieve the goals of the water users either to optimize water supply for irrigation or to reduce damage done by excess runoff.

1/ Hydrologist, Water Supply Forecast Staff, Soil Conservation Service, Portland Oregon.
2/ Water Supply Specialist, Soil Conservation Service, Bozeman, Montana.
3/ Water Supply Specialist, Soil Conservation Service, Reno, Nevada.

The reservoir operations tools developed by the Soil Conservation Service are available to anyone through the Centralized Forecasting System(CFS). These tools enable users to access and analyze daily reservoir inflow information to determine reservoir outflow settings. Three sets of curves are developed, each leading sequentially to reservoir rule curves.

The first set of curves are called storage-outflow curves. Storage-outflow curves attempt to quantify the relationship between seasonal streamflow volume and the magnitude of daily flows within the season. Each years reservoir inflows are analysed to determine the volume of water stored with various levels of outflow. In the analysis, the outflow cannot exceed the inflow (no draft) and storage occurs when the inflow exceeds the outflow.

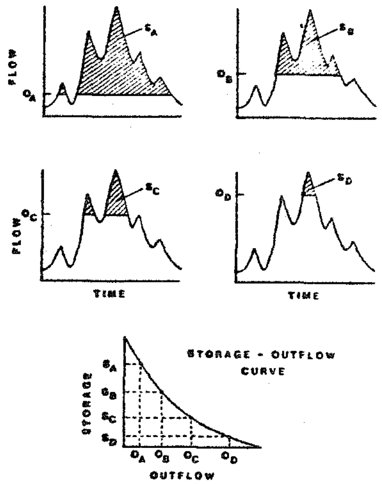


FIGURE 1

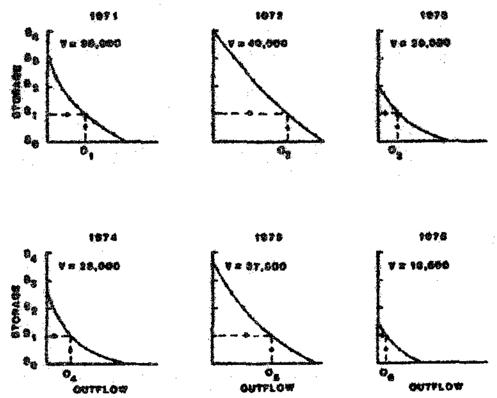


FIGURE 2

Figure 1 shows this procedure for a single year's hydrograph. As can be seen from the figure, setting outflows of O_A, O_B, O_C, O_D results in storing volumes S_A, S_B, S_C, S_D (cross-hatched area). The actual storage-outflow curve would be based on many more points than the four used in the example.

In figure 2 the results of six storage-outflow analyses are shown. This hypothetical example includes data from high, low and intermediate years, which is a basic requirement of any data set to be analyzed. Ten year's data is the minimum requirement, but fewer years may be used for a preliminary analysis if they include representative years and do not bias the analysis due to the dominance of either high or low years during the period (Shafer et al., 1986). These curves can be represented by fitting a 5th degree polynomial to the data points. The form of the polynomial is:

$$S = b_1O + b_2O^2 + b_3O^3 + b_4O^4 + b_5O^5 + b_6$$

where b_1 through b_6 are regression coefficients and S and O are storage and outflow respectively (Shafer et al., 1986). This technique is used in the computer program to describe each of the curves. Each year has a 5th degree polynomial fitted to it by analyzing a minimum of 75 individual outflow values and their corresponding storage values. Figure 3 shows the storage-outflow curve for one year on MacKay Reservoir, Big Lost River, Idaho. Once the storage-outflow curves have been established for each year in the analysis, a set of volume-outflow curves can be developed for the reservoir.

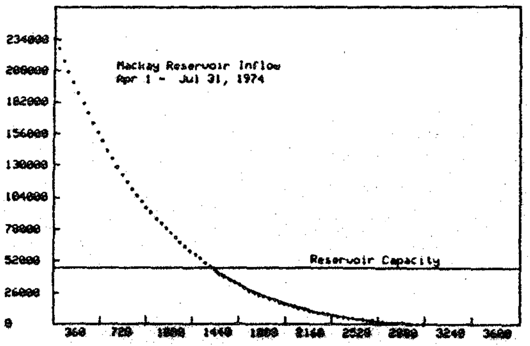


FIGURE 3

A volume-outflow curve is a graph allowing the operator to determine an outflow setting, given the remaining storage space in the structure and the expected volume for the period. The manual process for development of a volume-outflow curve involves a plot where each year is plotted matching the outflow rate with the volume for the period used at that particular forecast point, i.e. April 1-July 31. The Big Lost River inflow to MacKay Reservoir is an example of one of those forecast points.

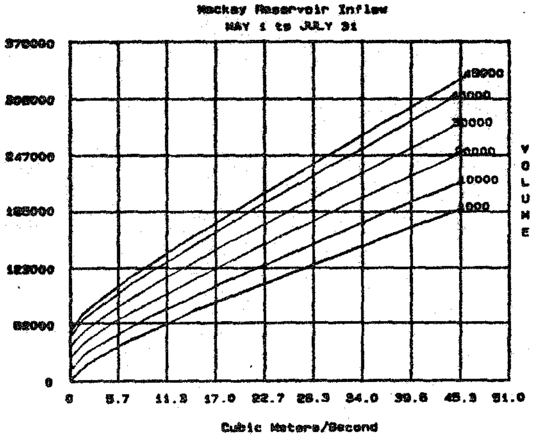


FIGURE 4

Each manually constructed graph contained a series of the desired target to store volumes and then the graphed points were fit by eye. Figure 4 shows curves generated by computer.

The data points for forecast-period volume versus outflow, given the remaining storage space in the structure, are generated by studying the storage-outflow equations of the previous analysis and the actual volume produced for the forecast point in that year and fitting those points to a curve represented by the equation:

$$V - S = a_1 O + a_2 O^{0.5} + a_3 OS$$

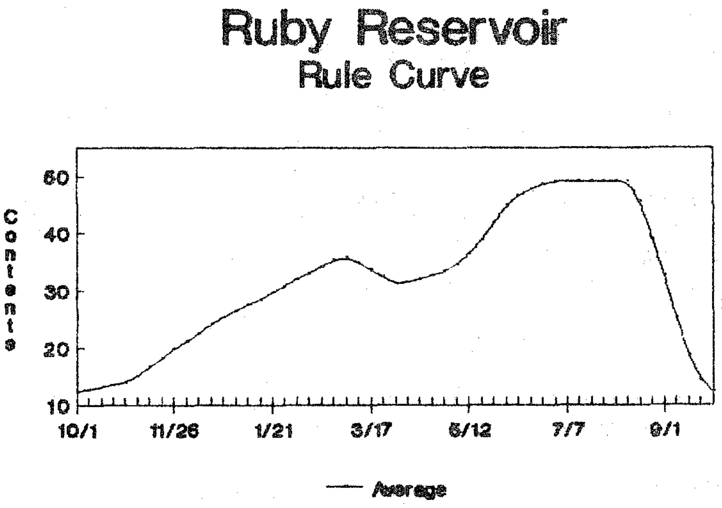
where V = total seasonal volume inflow to reservoir
O = outflow required to obtain desired storage
S = desired storage
a_1, a_2, and a_3 are all regression coefficients.

The variables are transformed to meet certain rational or observed behavior. When the seasonal volume equals the desired storage (left side = 0) the outflow is zero. The first independent variable (O) is set as a standard linear regression term. The second independent variable ($O^{0.5}$) is set to reflect the observed non-linear behavior between inflow volume (V) and outflow setting (O) for a given storage (S). The third independent variable (OS), reflects the skewness between the various storage level curves. The coefficients a_1, a_2, and a_3 can be determined by using either Gaussian elimination or matrix inversion simultaneous equations (Shafer et. al., 1986). Once the three coefficients have been determined, the volume-outflow curves can be generated. Each reservoir as well as each forecast period will have its own unique set of coefficients.

The Reservoir Storage Volume Planning(RSVP) process has thus defined the storage-outflow relationship and the volume-outflow relationship for each storage level. An outflow setting for a particular volume of water can then be determined for any desired storage level. At this point several assumptions of the RSVP process need to be reviewed.

The RSVP process assumes that as inflow rises toward the suggested outflow reading, the outflow is adjusted so that there is no storage gain or loss in the reservoir up to the point where inflow exceeds the index outflow rate. The overall result of this assumption is that the reservoir never drafts during the evaluated season and only stores water during days that the inflow exceeds the index outflow. The inflow-outflow assumption does not allow for modifications to account for operations that would minimize emergency spillway flow, increase the frequency of a full reservoir at a certain time of the year, or simple maximization the water available for irrigation.

Rule curves allow the user to modify outflow levels to achieve maximum irrigation supply, fisheries requirements, and minimal emergency spillway flow, streambank erosion and downstream flooding. The rule curves are derived through the expertise of the hydrologist and use of trial and error. During this process all years of data are reviewed using the established volume-outflow curves. The hydrologist can then determine whether the RSVP process has satisfied the user's operational goals and, if not, where it has failed. Historic data is broken down into two additional sets of data that describe those years above an upper bound, usually 130 percent of average, and another set of years that is below a lower bound, usually 70 percent of average. The upper and lower limits are dependent on the variability of the volume produced as well as the variability of flow during each month. The operational goals are then divided into those goals which would affect the upper set, the lower set, and those that would affect the average. A rule curve is then developed for the three sets individually. These curves can provide for reservoir draw down or increasing contents early in the forecast period. Figure 5 shows the average rule curve for Ruby Reservoir. This curve was derived from the average hydrograph and is satisfactory for volumes between approximately 90 percent of average and 110 percent of average.



Contents in 1000's of cubic dekameters

FIGURE 5

RESERVOIR CHARACTERISTICS

The three examples described here are: Ruby Reservoir, Ruby River Basin, Montana; MacKay Reservoir, Big Lost River, Idaho; and Wild Horse Reservoir, Owyhee River, Nevada.

Example 1. Ruby Reservoir

Ruby River inflow to Ruby Reservoir averaged 130,505 cubic dekameters April 1 through September 30 for the 1961 through 1985 period. The coefficient of variation for the 139,345 hectare watershed is 0.31 for the 49-year period of record. Variations below 0.40 are considered relatively stable with low variation in annual volumes. The only flows with lower variation are in the Pacific Northwest, mainly in the Coastal Drainages.

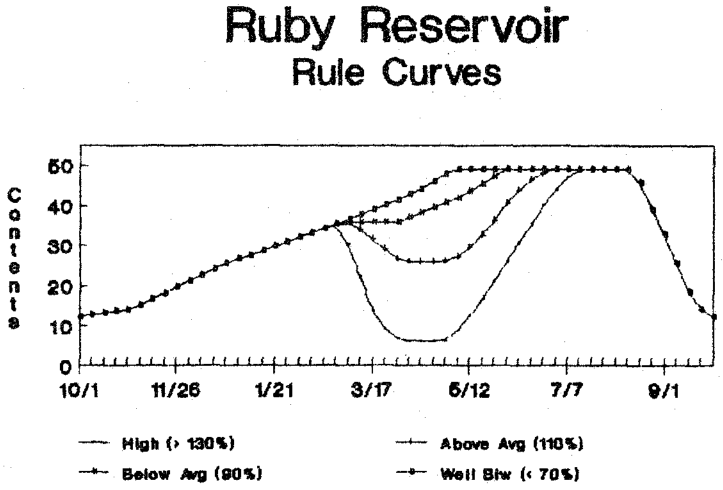
Snowmelt runoff from the Ruby River occurs in late spring and summer. In 1961, the lowest year of record, the maximum flows occurred in May, producing 31 percent of the annual total. At the opposite extreme, 1984, the maximum flows occurred in June producing 35 percent of the annual total. These maximums demonstrate the relative consistency of the watershed with a change from low to high years of only one month. In 1961 the Ruby River produced 45 percent of the annual irrigation requirement. 1984 runoff met 178 percent of the irrigation demand. It should be pointed out that in a low year, even though the watershed produced 45 percent of the average annual irrigation demand, actual irrigation demand was probably 50 percent higher due to higher temperatures and low precipitation over the irrigated area.

Frequency analyses show that the watershed has a 90 percent chance of producing at least 57 percent of the average annual irrigation demand and only a 10 percent chance of producing 120 percent of the average annual irrigation demand or more. The average annual irrigation demand is 134,450 cubic dekameters which is 103 percent of the average seasonal flow.

The operational goals for Ruby Reservoir are as follows:

1. Satisfy irrigation demands.
2. Fill the reservoir.
3. Release no more than 1.4 cms during the winter.
4. Keep downstream flows below 18.4 cms.
5. Reduce peak flows during high runoff year.
6. Minimize emergency spillway flows.

The Reservoir itself stores 44 percent of the average annual flow from the watershed. This makes it very difficult to manage the reservoir because rather substantial outflows are



Contents in 1000's of cubic dekameters

FIGURE 6

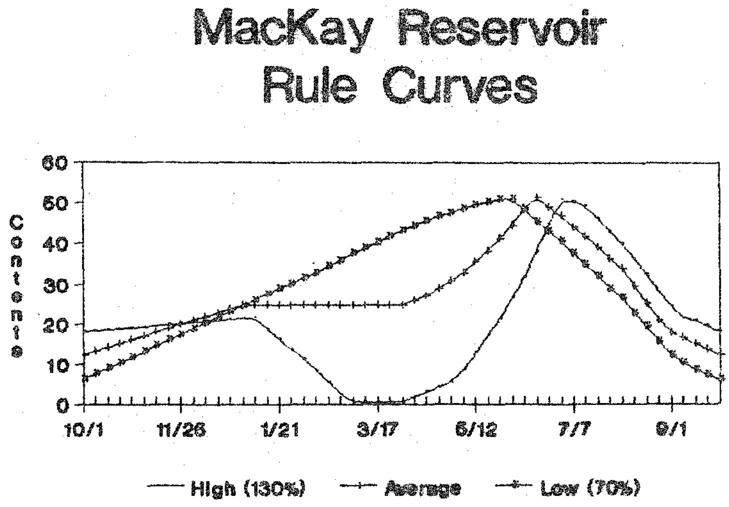
required in high years. Ruby is in an environment where excessive outflows prior to March 1 may cause flooding due to ice jams. In above average years, the reservoir must be drawn down dramatically between March 1 and the onset of snowmelt runoff to provide adequate storage space. In this area of Montana, actual draw down can extend through the middle or end of April. Figure 6 shows the rule curves for this structure illustrating the dramatic draw down necessary in years having more than 90 percent of average seasonal volume.

Example 2. MacKay Reservoir

April-September inflow for MacKay Reservoir averaged 239,545 cubic dekameters during the 1961 through 1985 period. The coefficient of variation for inflow to MacKay is 0.39 for the 37 year history. This watershed demonstrates slightly more variability statistically than Ruby River.

Runoff from the Big Lost River basin into MacKay Reservoir occurs in late spring to early summer. The low flow on the Big Lost occurred in 1961, with June, the maximum month, producing 52 percent of the annual volume. The maximum runoff occurred in 1965, with June producing 39 percent of the annual volume. Even though the coefficient of variation is higher for the Ruby River, the Big Lost River is much more consistent in terms of timing. The maximum runoff occurs in June 95 percent of the time.

The reservoir itself stores about 20 percent of the average annual runoff from the Big Lost River Basin. MacKay Reservoir is more difficult to manage under high flows because of the small proportion of the runoff it can hold. Draw down on MacKay is less restrictive than on Ruby Reservoir because draw down can begin very early. Figure 7 shows the resulting rule curves for MacKay reservoir.



Contents in 1000's of cubic dekameters

FIGURE 7

The operational goals for MacKay Reservoir are:

1. Satisfy irrigation demands.
2. Maintain flow downstream below 42.5 cms.
3. Reduce peak flows during high runoff year.
4. Fill the reservoir.
5. Minimize emergency spillway flows.

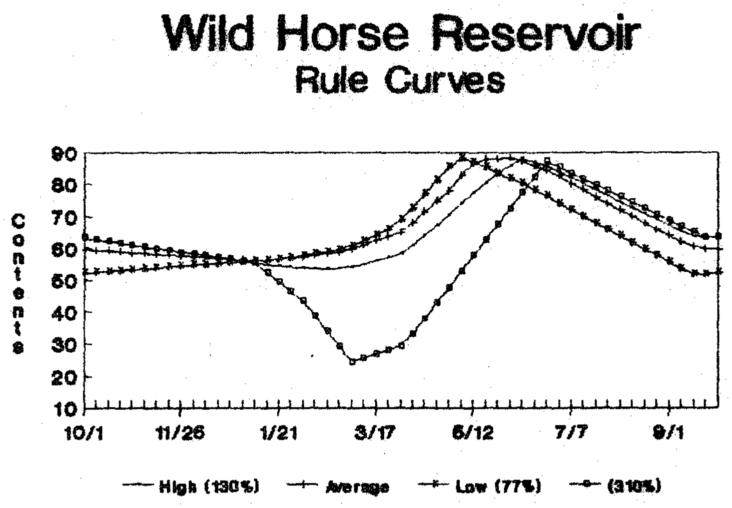
Irrigation demand on the Big Lost River is 201,480 cubic dekameters and has been satisfied 64 percent of the time. Reservoir inflow averages 270,134 cubic dekameters for the irrigation period. Reservoir inflow has been less than the irrigation demand 14 times since 1951 and represents the 60 percent chance of exceedance. Like Ruby Reservoir irrigation demand is only critical in low years.

Example 3. Wild Horse Reservoir

Wild Horse Reservoir represents the extreme in variability. The Owyhee River, inflow to the reservoir, averaged 49,095 cubic dekameters for the March 1 through September 30 period during the years 1961 through 1985. The coefficient of variability for the Owyhee River inflow to Wild Horse is 0.70. This is an extremely variable stream when compared to the previous sites.

Maximum runoff from the watershed can occur from early March to late May but the runoff seldom occurs beyond the last part of May. The minimum runoff occurred in 1981. About 36 percent of the volume was produced in March, but the total volume was only 10 percent of average and irrigation demand. Irrigation demand equals the average runoff for the March-September runoff period.

The maximum runoff occurred in 1984. The watershed produced 151,840 cubic dekameters or 309 percent of the average volume. The only other point of consideration is that the entire snowmelt hydrograph can be completed in as little as two weeks and rarely exceeds 8 weeks. March flows exhibit the highest variation of any month. March flows can account for as much as 90 percent or as little as 5 percent of the seasonal volume. This variability can occur in any year depending on weather conditions during March. Figure 8 shows the rule curves for Wild Horse Reservoir.



Contents in 1000's of cubic dekameters

FIGURE 8

The operational goals for Wild Horse Reservoir are:

1. Reduce peak flows during high runoff year
2. Minimize emergency spillway flows
3. Maintain flows downstream below 8.5 cms
4. Fill the reservoir
5 Stabilize contents for recreational uses
6. Satisfy irrigation demands

SIMULATED RESULTS

Ruby Reservoir

Figures 9 and 10 show the observed outflow and the outflows projected from the use of the rule curves of Ruby Reservoir, Montana in 1984. Peak flows in 1984 could have been reduced by 10 cubic meters per second through the use of rule curves(see figure 6).

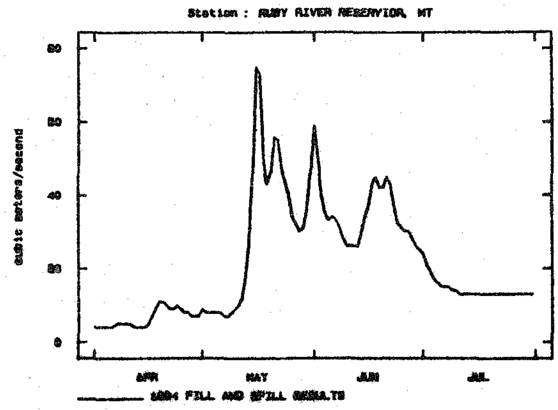


FIGURE 9

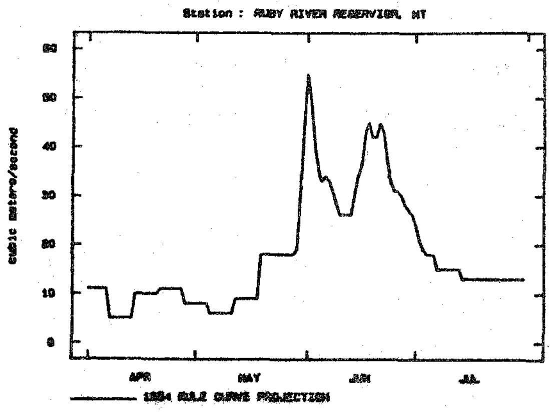


FIGURE 10

Ruby Reservoir has remained quite full in high years and therefore a recommendation for operational criteria, increased outflows, and increased available storage can be drawn from the rule curves. The results observed and projected from the use of the high forecast rule curve are shown in figure 11 and figure 12 respectively.

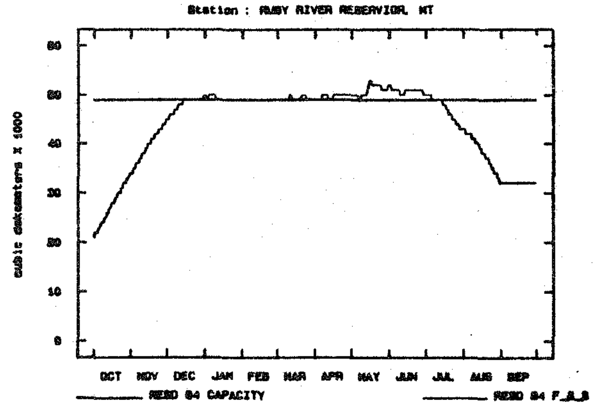


FIGURE 11

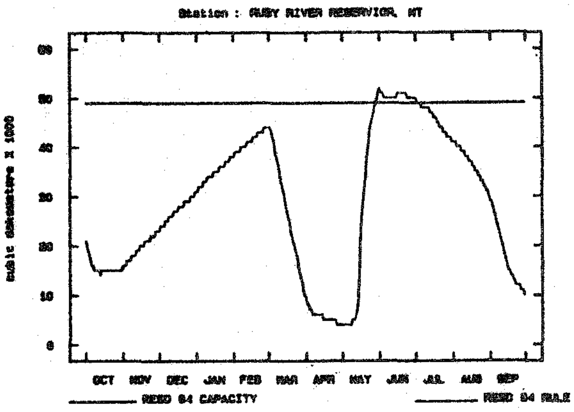


FIGURE 12

In low years, for example 1977, the flows can be distributed more evenly through the irrigation season and still provide irrigation equal to that achieved by filling the reservoir early. The figures show reservoir operations without rule curves (figure 13) and with rule curves (figure 14).

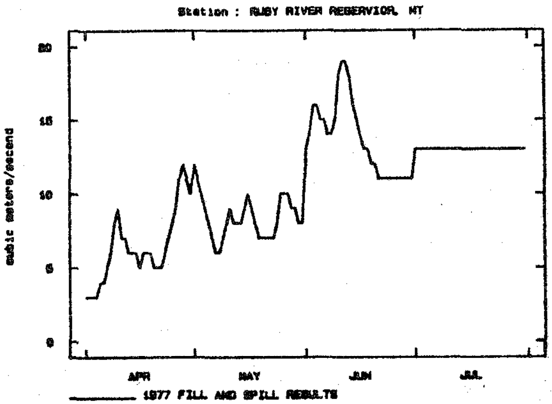


FIGURE 13

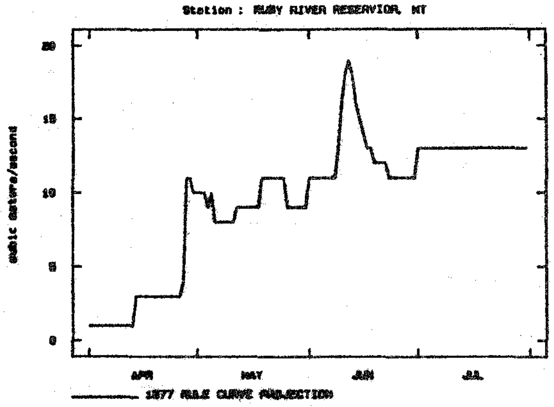


FIGURE 14

MacKay Reservoir

Figures 15 and 16 show the observed outflow and projected outflow using the rule curves for MacKay Reservoir in 1984.

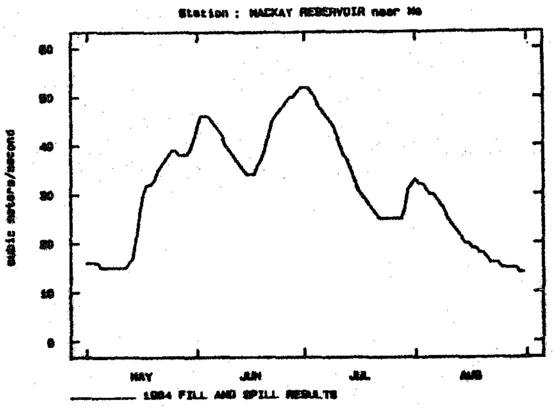


FIGURE 15

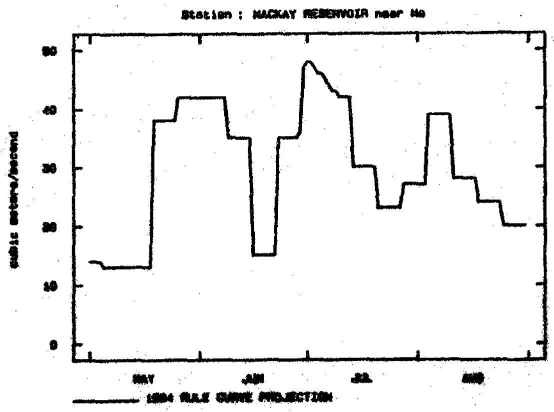


FIGURE 16

The most significant problem in managing MacKay Reservoir is handling high flows because of the capacity of the structure in relation to the runoff. Even the lowest of year's runoff will exceed the storage capacity of the structure.

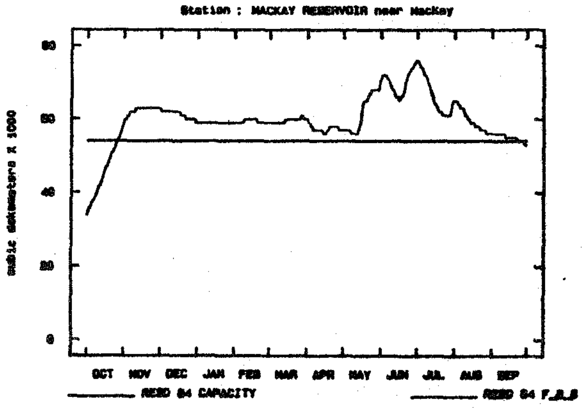


FIGURE 17

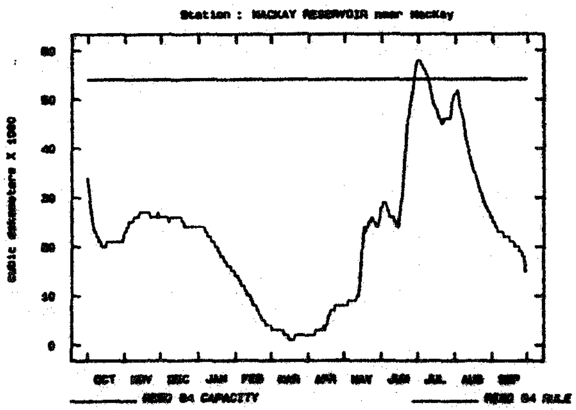


FIGURE 18

Figure 17 shows the reservoir contents in a very high year, 1984, and Figure 18 shows the result of the rule curve application (figure 7).

Wild Horse Reservoir

Figure 19 shows the observed outflow of Wild Horse Reservoir in 1984 and figure 20 shows the projected application of the rule curves(see figure 8).

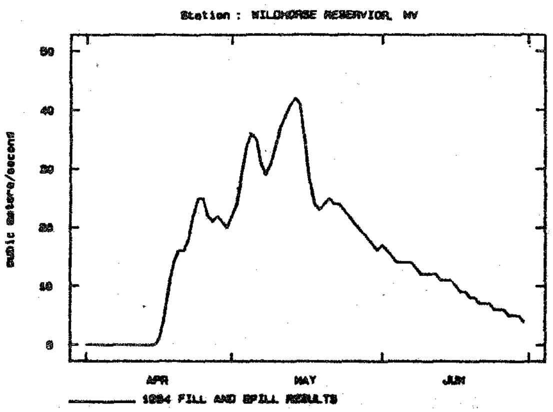


FIGURE 19

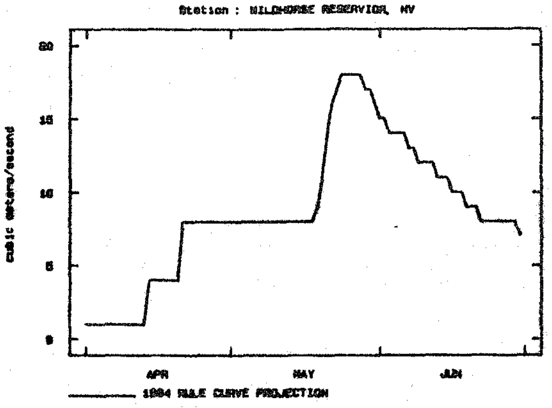


FIGURE 20

Wild Horse Reservoir stores approximately 2 year's water supply for the Duck Valley Indian Reservation. Consequently, as reflected in the goals for the structure, the main concern of operators is being able to handle high flows.

SUMMARY

The Reservoir Operations Guides then provide the user with an alternative to fill and spill. The Guides are oriented to the small reservoir operator. They provide for informed decisions based on statistically sound volume forecasts. Operations curves are objectively derived. Guides provide for operations decisions with provision for operations goals. Finally, Reservoir Operations Guides provide managed exposure to risk for the small operator.

REFERENCES

Carnahan, B., H.A. Luther, and J.O. Wilkes, 1969. Applied Numberical Methods. John Wiley & Sons, New York, N.Y.

McCuen, Richard H., 1985. Statistical Methods for Engineers. Prentice-Hall, Inc., Englewood, N.J. pp. 221.

Shafer, B.A., P.E. Farnes, K.C. Jones, J.K. Marron, and F.D. Theurer, 1986. Reservoir Operations Planning in Snowmelt Runoff Regimes Based on Simple Rule Curves, Cold Regions Hydrology Symposium, American Water Resources Association, Fairbanks, Alaska, pp. 13-22.

Soil Conservation Service, 1989. Reservoir Operation Guides Technical Release. United States Department of Agriculture, Soil Conservation Service, Washington D.C.