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# Methods for Determination of Safe Yield and Compensation Water from Storage Reservoirs

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The simple mass-curve types of analyses are no longer practical for the design of reservoir projects because of the complex operation factors that must now be considered. The procedures used in reservoirs of all types and of regulated streamflows downstream of reservoirs consist generally of detailed routing studies using historical streamflow sequences. There is considerable effort currently being devoted to investigating the potential application of stochastic hydrology to reservoir planning and design studies.

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US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center
609 Second Street
Davis, CA 95616

(530) 756-1104
(530) 756-8250 FAX
www.hec.usace.army.mil

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# METHODS FOR DETERMINATION OF SAFE YIELD AND COMPENSATION WATER FROM STORAGE RESERVOIRS (a)

LEO R. BEARD (b) - U.S.A.

## INTRODUCTION

Methods used in the United States for the determination of safe yield from reservoirs are governed by the complexity of the water resources development project. It is rare when simple mass-curve types of analysis are practical, as they may have been in years past. The trend toward multiple use of reservoir space and the consideration of prior rights and legal restrictions dictate that a detailed sequential analysis of inflows, outflows and other operation factors be made.

In general, the same principles are used in the determination of reservoir yield, regardless of the nature or type of water supply reservoir. The three types of reservoirs considered are designated for purposes of this report as: impounding reservoirs from which water supply is piped direct to destination, regulating reservoirs from which water is released to the river for downstream use, and pump storage reservoirs, into which water is diverted or pumped from the river for future use.

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(a) For use in preparation of General Report No. 2 for Seventh International Water Supply Congress, Barcelona, Spain, 3-7 October 1966. Not for publication as a separate paper without prior approval of the Chief of Engineers, U.S. Army.

(b) Chief, Hydrologic Engineering Center, Corps of Engineers, U.S. Army, Sacramento, California.

The basic procedure used throughout the United States consists of performing a reservoir routing study or reservoir simulation study, with the assumption that historical inflows (exact historical sequences) will recur in the future, or that they represent an adequate test for design purposes. It has been recognized for many years that this assumption leaves much to be desired. It has been demonstrated, for example,(5) that storage determinations based on different halves of the same long records differ by a factor of 2 or more in half of the cases where high firm yields are required. Accordingly, considerable work has been done toward simulating streamflow sequences, with the expectation that a number of artificial sequences can be studied rather than the single sequences of record, thus providing more dependable estimates of firm yield. However, there is no record in literature of an actual design being based on such simulated streamflow series.

## IMPOUNDING RESERVOIRS

Analysis of firm yield for a single impounding reservoir (i.e., from which water is piped direct to destination) represents a relatively simple type of yield analysis. However, even such projects usually present complex problems. Inasmuch as the seasonal variations of runoff and of use are different, the application of some simplified procedures are impractical. Evaporation and other losses are often an important element, and cannot be determined accurately without a detailed analysis of reservoir stages. Where power generation is included as a project function, reservoir stages also affect the amount of release from time to time.

Where storage is to be provided only for seasonal and short-term regulation of runoff (where water need not be retained from one year to the next), yield determinations can in simple cases be based on studies of the frequency of low flows. Frequency curves of annual minimum runoff volumes for durations ranging from a few days to a year can be used to establish the probability of drought. For a specified probability, a curve of minimum runoff versus duration can be constructed. A straight line with slope equal to the desired yield is then made tangent to this curve, and the negative intercept of that line represents the required storage. This type of analysis is simple and introduces the probability concept, but is practical only in cases where water use does not vary seasonally.

Duration curves of runoff are used in some cases of design for run-of-river power plants, but are of decreasing value, because of seasonal and short-term variations in power requirements. They are not used effectively in water yield studies.

For long-term storage (storage carried for more than 1 year) and for short-term storage where there is seasonal variation in use, the simplified analysis represented by the Rippl diagram might be used. However, as stated above, complex variations in evaporation, power generation, water rights, flood control, and other factors usually justify the more detailed analysis wherein a month-by-month routing (operation simulation study) showing reservoir stages, evaporation, and other factors as well as inflow and outflow is made. Usually such routings are made on a monthly basis, with special consideration being given to daily variations in supply and to flood control.

Even in the case of single impounding reservoirs, there are often factors to be considered that require detailed studies of sequences. Stages of the reservoir during the recreation season and during the flood-control season are often governed by conditions of authorization. Some stage fluctuations for mosquito control may be required. There is usually a requirement to release water to the river to satisfy prior rights, quality control and fish requirements. The temperature of water released for fish, industrial purposes, or irrigation may impose some restrictions on the reservoir operation stage. This item has become increasingly important in recent years.

In general, then, the determination of safe yield from impounding reservoirs might be based on simple procedures such as the low-flow frequency analysis and Rippl diagram, but would usually be based on a detailed study of streamflow sequences, using reservoir routing procedures, because of the complexity of many of the factors affecting reservoir operation. Such a study is outlined in the section entitled "General Procedure".

## REGULATING RESERVOIRS

Determination of safe yield and compensation water (low-flow regulation) for regulating reservoirs is considerably more complex than yield determinations for impounding reservoirs. This is generally due to the fact that uses at the diversion point can be satisfied fully or in part by runoff contribution from areas tributary below the reservoir. Also, there are cases where percolation loss in the channel between the reservoir and the point of diversion greatly affect the supply. Accordingly, it is general practice in the United States to base yield determinations for regulating reservoirs on detailed monthly routing studies, giving due consideration to runoff intermediate between the reservoir and diversion point or points and to percolation losses in the channel, where appreciable.

In many cases of regulating reservoirs, there are interests who own water rights that are not being served by the project. Often such water rights have a variety of priority, sometimes intermixed with those served by the project. Consequently, it would be theoretically necessary to perform day-by-day analysis of inflows to determine the daily amounts of water owned by project entities and surplus water that can legally be stored in the reservoir. However, this is usually accomplished on a monthly basis, using approximate relationships derived from examination of daily streamflows. When periods of low flow occur in the operation of regulating reservoirs, streams contributing below the reservoir, as well as inflow to the reservoir, are low. The requirement at the point of diversion is satisfied only by releasing sufficient water to overcome the shortage of intermediate flow as well as to provide the supplemental supply. Thus the regulating storage requirement is a function of total supply above the point of diversion less that portion of the intermediate runoff that exceeds the requirement at the point of diversion.

Regulating reservoirs usually serve more than one function; consequently there is more frequent need for detailed analysis of this type of reservoir. The routing or simulation study can involve dozens of columns containing variables concerned in the study. A complete simulation study would include consideration of the monthly requirement at each point of diversion, varying runoff contribution and losses between these points and the reservoir, flood control and power requirements at the reservoir, flows or stages at critical river locations downstream of the reservoir where flood control, water quality, navigation, or fish requirements are specified, evaporation from the reservoir, and the deliveries to each point of diversion where prior water rights must be satisfied.

In general, then, it can be stated that determination of safe yield for regulating reservoirs usually requires a detailed monthly analysis of many factors. Such analysis is similar to, but usually more complex than, analyses for impounding reservoirs.

## PUMPED-STORAGE RESERVOIRS

Pumped-storage or off-stream reservoirs usually serve a single purpose, and are consequently more easily studied than are the other two types of reservoirs. In general, all water above river flows required to satisfy prior rights can be diverted to the reservoir, up to diversion or pump capacity rates. Inasmuch as prior rights usually vary seasonally and often with rate of streamflow, and pump or diversion capacity may vary with head, simplified procedures cannot always be applied in such safe-yield

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determinations. In general, a monthly routing of streamflows at the point of diversion and through the proposed reservoir is required. Such a routing or system simulation study would be similar to those made for the more complex studies of impounding and regulating reservoirs.

## GENERAL PROCEDURE

Detailed routing studies require considerable time and effort, but this is of minor consideration in relation to other project design and construction requirements. Performance of a detailed project routing or simulation study is accomplished in the following steps:

a. Determine non-project streamflow at each reservoir site and at downstream points of diversion. Non-project conditions (often termed pre-project conditions) are defined as those that are expected to prevail during the lifetime of the proposed project if the project is not built. This determination requires consideration of all non-project reservoir and diversion effects in the river basin that may differ in the future from their historical effects. It also requires estimating streamflows where records were not obtained and estimating the effects of known future water regulatory structures that will be built whether or not the contemplated project is built.

b. Determine monthly firm supply required at each reservoir and at each point of diversion or point of low-flow regulation. Where these values depend on streamflow or runoff, as in the case of some water rights, they may be expressed as a function of those quantities. Power requirements at a reservoir may be expressed as energy so that reservoir release requirement would depend on reservoir head at the time. Quality-control requirements may be expressed in parts per million maximum concentration of various pollutants, so that reservoir releases would depend on the amount and quality of water downstream as well as quality of released water.

c. Determine monthly reservoir stage limitations governed by flood-control, recreation and minimum-power-pool requirements. Reservoir level and release fluctuations for mosquito abatement should be considered, if appropriate.

d. Determine expected average monthly evaporation and seepage loss expressed as a depth over each reservoir area for each calendar month. This would ordinarily represent losses over and above those experienced in the reservoir area under non-project conditions, and can be negative under some circumstances.

e. Develop relation of river percolation losses to rate of flow, where such losses appreciably affect delivery quantities. Where necessary, antecedent channel conditions must be considered.

f. Develop multi-reservoir operation criteria. Where a water requirement can be served by more than one reservoir, develop rules for month-to-month selection of reservoir for such supply. These would be based on the existing reservoir stage in relation to multipurpose requirements at each reservoir and may vary seasonally.

g. Establish criteria for allowable shortages. These may differ for different types of supply such as irrigation, municipal, industrial, power, navigation, quality control, etc. Rules for declaration of shortages should be in terms of information that would be available during actual operation.

h. Establish initial reservoir stage. Ordinarily, a project is designed on the basis of requirements during the most severe drought period recorded, and the initial reservoir stage for each reservoir is selected as full to top of conservation pool (bottom of flood-control space, if any) at the start of that period. As a more general rule, the reservoir should be assumed empty at start of operation, as it will be in actual use, when tested over its entire expected lifetime.

i. Perform routing operation, determining first the month-by-month release required from each reservoir to satisfy all needs and then subtracting the release and evaporation and seepage losses from the sum of storage and inflow. Where storage is inadequate to supply a requirement or where rules call for a shortage, tabulate the amount of shortage.

The routing study can be complicating by factors such as variable water-quality requirements related to flows of highly saline streams, along with incomplete mixing within each reservoir, varying and differing water temperature requirements for fish, irrigation and industry, and the necessity to forecast streamflows intermediate between the reservoirs and diversion points and into the reservoirs when shortages are pending or when surpluses might be declared. Irrigation requirement in actual practice will depend on rainfall in the agricultural area. One inch of rain more or less over 50,000 acres of irrigated area can change the reservoir release requirement by 4,000 or 5,000 acre-feet. Because of the many complicating factors, it is essential that the routing study include contingency allowances for operation uncertainties in order to assure realistic simulation of actual operating conditions. These are sometimes introduced as a minimum storage pool to be used in extreme emergencies only, but are more realistically introduced as error allowances in each component operation.

## ALLOWABLE SHORTAGES

The safe yield provided by a reservoir is usually defined as the annual flow delivered by the project without causing intolerable shortages under recurrence of historical droughts. In the case of municipal and industrial (M&I) supplies, it is usual practice to permit no shortage, and in some cases even to provide a reserve storage in the event of droughts that exceed the worst of record. In the case of irrigation supplies, shortages can usually be anticipated and can be sustained at infrequent intervals. Some irrigation projects have been designed to permit shortages of 25 to 35% in 4 of the years during the most severe drought of record. One-year shortages as large as 50% have been permitted. It has been found that a 10% irrigation shortage usually results in little or no damage, that a reduced crop can be obtained with a 25% shortage, and that perennials can be sustained without a usable crop during a season of 50% shortage. These findings would vary, of course, with types of crops, irrigation practice and geographic location.

There is increasing recognition of the fact that shortages more severe than the worst historical drought can occur. This is leading toward design criteria based on probability of shortage or expected shortage. Quality control determinations are usually based on the probability that supplies will meet required streamflows. Beyond this, there has been very little application of probability or expected-shortage criteria in the design of actual projects in the United States. As studies of streamflow simulation come into use in reservoir design, such criteria will be essential, because it is always possible that a more severe sequence of flows will occur than has heretofore been observed or anticipated. A convenient shortage index has been proposed(4) that should be helpful in design and planning studies. This is the sum of the squares of annual shortage ratios over a 100-year period. An index of 1.0, for example, would permit 100 10-percent shortages or four 50-percent shortages or one 100-percent shortage in 100 years. A more sophisticated treatment would balance cost of additional storage against benefits expected from decreased shortage.

## NEW APPROACHES

The need for new approaches that eliminate the assumption of recurrence of historical streamflows in the exact sequences of record is obtaining increased recognition in the United States. During recent years, procedures of yield analysis such as the queueing theory have been developed. This theory or procedure utilizes the concept of probabilities of inflows and resulting probabilities of storages and outflows in such a manner that storage determinations are independent of exact historical sequences. The procedure is practical only for simple cases where use is uniform and where factors such as reservoir evaporation, flood control, etc., are not significant. There are no published cases of actual design by such methods.

Increasing attention is being given by universities and water resource agencies to the potential application of streamflow simulation procedures (stochastic hydrology) to reservoir planning and design studies. Essentially, historical runoff is analyzed into its various frequency and correlation characteristics. Frequency and correlation characteristics derived from recorded data are then used to generate new series of correlated events that can as likely occur in the future as could recurrence of historical events. In this manner, numerous complete sequences of streamflows can be used for project analysis, instead of one historical set of data that usually are partially estimated and of duration shorter than desired for analysis. Such hypothetical (or synthetic) flows are of reliability limited by sample uncertainties of recorded data, but provide a greater variety of potential sequences and consequently permit more dependable estimates of safe yield.

Design procedures employing simulated streamflows would be identical to the detailed routing procedures that employ historical streamflows as a basis for study. Although no actual design based on simulated streamflows has been reported in literature, current thinking is that analyses would be based on historical streamflows as well as 10 or 20 simulation sequences of 50 to 100 years each. The determinations based on each of the many series would be compared and can reveal potential weaknesses of some of the contemplated designs. Ultimately, expected-benefits or expected-yields, representing the average accomplishment indicated by many simulation sequences, might be adopted as a basis of design.

Use of simulated streamflows in design would greatly increase the amount of computation required. Consequently, it will be necessary that routing or system simulation studies would be accomplished by use of electronic computers. Once a routing study is programmed for electronic computers, it will be feasible to make many studies of different components in the design, inasmuch as the computation work becomes relatively inexpensive. A few computer programs have been developed for this purpose in the United States. These have been designed essentially along the lines of the hand computation procedures and are used for routing historical streamflows.

It has been found that "digesting" the results of computer studies requires far more time and expense than does computation of the results in the computer. Consequently, there is increasing attention being given to potential optimization of project accomplishments within the computer. This will consist essentially of formulating equations or computation procedures expressing project accomplishments as a single index (the objective function) in terms of various project components. By repeated analysis of the system and calculated changes in each component, the computer would maximize the accomplishments index. Although much "optimization" work is in progress, only a few reports on the subject have been published.(8,11,13)

# CONCLUSION

In summary, it can be stated that procedures used in the United States for determination of safe yields from reservoirs of all types and of regulated streamflows downstream of reservoirs consist generally of detailed routing (simulation) studies using historical streamflow sequences, modified for expected non-project changes, as a measure of what may occur in the future. There is considerable effort currently devoted to obtaining more dependable measures of potential streamflow by use of streamflow simulation procedures.

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