FIRM WATER AND SHORTAGE INDEX IN WATER SYSTEMS PERFORMANCE ANALYSIS

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Abstract

The annual firm water yield and distribution shortage index represent the important systems analysis issues common for studies related to performance analysis and reservoirs' control within large-scale water resources systems. Simulation and mixed optimization/simulation are typical techniques used in such analyses, whilst computed surface reservoirs' storages are always 'measured' with respect to some prespecified targets, preferences or simply 'wishes'. Systems approach helps to select and apply appropriate methods to define tolerant deviations from the targets and to recognize favorable and not-favorable system statuses. In this way it enables computing certain performance indices which describe system's, and particularly reservoirs', performance in long-term sense. As a consequence, control strategies applied in simulation or other models may be evaluated in more sophisticated manner and decisions can be significantly rationalized and judged.

Keywords: Performance, firm yield, shortage, system, reservoir

1. INTRODUCTION

Water resources systems with surface reservoirs has been seriously investigated by systems analysts in diversified directions. Numerous techniques has been applied recently for optimization, simulation and mixed simulation and optimization to demonstrate systems' performance on long term basis for applied operating strategies in order to help systems analysts and decision makers to recognize systems' behavior in normal and so-called hazardous conditions.

As reported in many studies, optimization techniques such as DP, LP and NetP proved to be an effective tools, but usually unexpectedly time consuming and/or costly /6/. Therefore, simulation techniques appeared to be prevailing in last two decades, especially if some optimization was included at any, even minimum, extent. A good example of such combination is set of mixed simulation/optimization techniques based on LP network optimization on the month level, and sophisticated intermonths balancing procedure which is in fact true simulation.

Different issues has been of interest recently as far planning and control of complex water systems with reservoirs are concerned. Modern performance analysis of such water systems generally goes as far to include reliability-risk (RR) evaluation of the reservoirs' long-term behavior on isolated (local) and aggregated (system) level /4/. RR concept is usually followed by other two, well known concepts of resiliency and vulnerability thus forming a frame for modern performance analysis of reservoir systems on long time-scales.

However, in any ambitious systems analysis other performance indices should not be avoided. The two of them have an absolutely superior significance. As indicated in /3/, annual water firm yield (and it's reliability) has been proven as one of the most important descriptor of the reservoir performance on long term basis. The other one, shortage index /3/, represents an excellently defined statistical parameter which aggregates in the same time shortage volumes and their frequencies of occurrence. Even traditional, those two performance indices are also important because decision makers are not always quite familiar with new terminology and demonstrate resistance to relatively new concepts such as risk, resiliency and/or vulnerability /1,2,5/.

2. ANNUAL FIRM YIELD

The annual firm yield (***FY***) is usually defined as the volume of water assured for delivering at some systems' "outlet" with acceptable shortage. In a background of this definition stands an assumption that water has to be delivered for sure and from year to year at some fixed and equal total volume, neglecting internal (monthly or seasonal) variations. ***FY*** may be computed for the exact systems' output point and for selected points within a system as well. In the first case provided is an information on systems total delivering capacity and it's reliability. The other case relates to some specific part of the system, such as particular reservoir itself, and computed ***FY*** indicates reliability of that part to be involved in overall water distribution within a system.

In computing ***FY*** it is necessary to specify an acceptable (tolerant) annual shortage of water (***S***), expressed usually in volumetric units, same as ***FY***, or simply as a percentage of ***FY***. In fact, ***S*** may be defined in different ways. The following example will help to understand the concept. If by assumption simulation of the reservoir system has been performed over the period of N consecutive years, and simulation results related to water demands, supplies and reservoirs' balances are gathered to identify shortages in deliveries, it is possible to identify the set of total annual shortages at given (outlet) point:

$$\{ s_i \mid i=1,\ldots,N \} \quad \ldots \ (1)$$

Total annual shortage s_i is an undelivered volume of water during the i-th year with respect to target annual demand D, and is defined by:

$$s_i = D - d_i \quad \ldots \ (2)$$

where d_i is delivered water in i-th year.

The acceptable annual shortage $\boldsymbol{S}$ may now be defined as maximum annual shortage occurred during the simulation:

$$\boldsymbol{S} = \underset{i}{\text{Max}}\ s_i \qquad \dots\ (3)$$

An alternative definition can be used starting from the unbiased mean estimate given by a relation:

$$\boldsymbol{S} = \frac{1}{N}\sum_{i=1}^{N} s_i \qquad \dots\ (4)$$

where each s_i and $\boldsymbol{S}$ are obviously strictly related to firm water $\boldsymbol{FY}$.

Once $\boldsymbol{S}$ has been computed, the reliability of firm water is easy to define as:

$$r_{FY} = 1 - \frac{\boldsymbol{S}}{\boldsymbol{FY}} \qquad \dots\ (5)$$

To compute reliability r_{FY} by use of (5) and (3) or (4) it is necessary to take into account all recorded annual shortages (including zero shortages, too!), and by definition D is equal to $\boldsymbol{FY}$. In fact, $\boldsymbol{FY}$ may be given in advance as estimate and simply forwarded as an input to the simulation model. Acting as a demand, $\boldsymbol{FY}$ is dynamically used as target for water deliveries and at the same time as the measure of system performance due to firm waters. The alternative approach is to instruct the simulation model to establish $\boldsymbol{FY}$ by iterative procedure itself, and than use it as previously described demand. The last one has been reported in /4/.

Finally, it should be noted that annual firm yield $\boldsymbol{FY}$ and it's reliability r_{FY} represent integral performance descriptor for the system on long-term basis. To some extent, it is a referent one for other performance measures.

3. SHORTAGE INDEX

This performance index represents the metrics of frequency and quantity of annual shortages occurred during system operation over N years. If the sum of monthly water demands during the i-th year is denoted as d_i, and the sum of recorded monthly shortages denoted as s_i, than shortage index may be defined as:

$$\boldsymbol{SI} = \frac{100}{N}\sum_{i=1}^{N}\left(\frac{s_i}{d_i}\right)^2 \qquad \dots\ (6)$$

The meaning of the shortage index may be explained by the following example: Let the total system demand in each of N = 50 years is equal to 10^6m^3, i.e. $d_1 = d_2 = \dots = d_{50} = 10^6$m^3 . Due to (6) shortage index is equal to:

$$\boldsymbol{SI} = \frac{100}{50}\sum_{i=1}^{50} s_i^2 = 2 \sum_{i=1}^{50} s_i^2$$

where s_i is given in $10^6 m^3$. Assuming that the shortage of $10^5 m^3$ has been occurred in 25 out of 50 years, which means that system has been delivering 10% less of water than demanded, then the value of ***SI*** is:

$$\boldsymbol{SI} = 2 \cdot 25 \cdot (0.1)^2 = 50 \cdot 0.01 = 0.5.$$

For annual shortage of 20% it follows:

$$\boldsymbol{SI} = 2 \cdot 25 \cdot (0.2)^2 = 50 \cdot 0.04 = 2$$

and for shortage of 40% we have:

$$\boldsymbol{SI} = 2 \cdot 25 \cdot (0.4)^2 = 50 \cdot 0.16 = 8.$$

For the same frequency of shortage occurrence, shortage index ***SI*** is quadratically dependent on shortage quantity. However, for the same shortage quantity, ***SI*** is linear function of shortage frequency. This situation is depicted on Fig.1.

Parametrized curves shown in Fig. 1 may be exploited in different ways. The one is to evaluate and gain better understanding of the influence of frequency and/or values of shortages in deriving the value of shortage index ***SI***. The other one is to compare outputs of simulation model for different operating policies and long-term strategies applied for reservoirs and make engineering or decision making judgments. The paradigm of the last one is the following example: the same value ***SI*** = 4 is obtained if annual shortage of 30% has been occurred in 45% of total number of years (i.e. in 22 out of 50), and if annual shortage of 50% has been occurred in 16% of total number of years (i.e. in 8 out of 50). It follows that the "best control strategy" may arbitrarily be selected for preferable combination of r and f parameters in fact without true optimization.

4. CONCLUSIONS

Appropriate formulation of a control problem for large-scale water resources system starts with extraction of control and state variables. Later on, when optimization or simulation of the system's performance should start, together with operating policy (set of rule curves for reservoirs, priorities of demands, etc.) additional criteria and related descriptors (indices) for measuring system's performance -- firm water, shortage index, reliability, risk, resiliency and vulnerability -- may be introduced. The last four belong to a class of so-called modern performance indices and are well documented in pertinent literature.

This paper deals with the first two above mentioned performance indices: (1) annual firm yield and (2) shortage index. In systems analysis they are usually recognized as traditional performance indices, unavoidable in serious reservoir systems' planning and particularly in evaluating control strategies and operating policies.

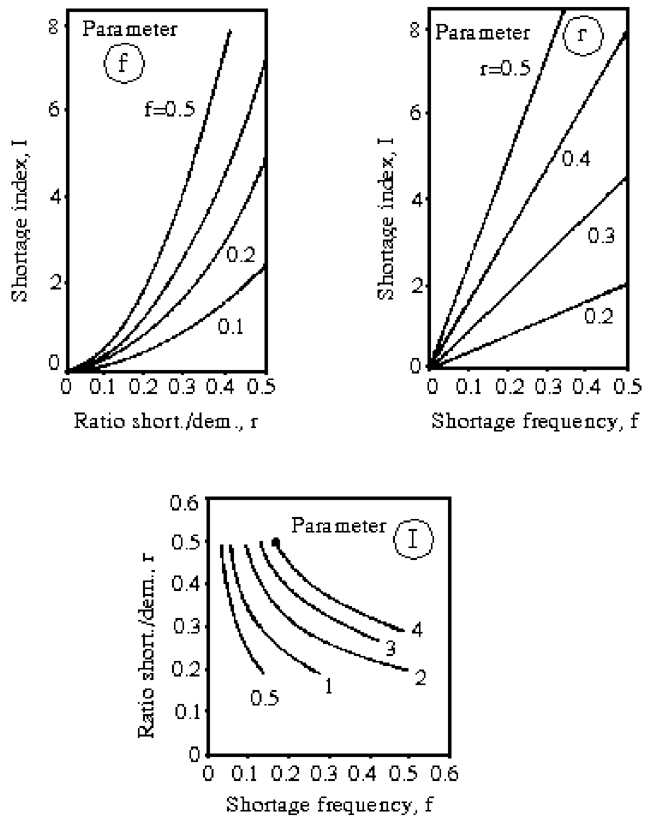

Fig.1 Parameter curves related to Shortage Index

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