Annual Journal of Hydraulic Engineering,
JSCE VOL. 40 (1996)

Inflow Forecasts: A Powerful Tool for Sustainable Reservoir Development and Management

By Vanchai SIVAARTHITKUL* and Kuniyoshi TAKEUCHI**

Old concepts in planning, operation and management need to be revised in order to fulfill the purpose of sustainable development. This study proposes to utilize the inflow forecasts as a tool for drawing the maximum use of storage as an aid to sustainable reservoir development and management. The inflow forecasts under different levels of forecast accuracy and lead time are applied to various sizes of reservoir and demand scenarios via optimization techniques. It was found that small reservoirs are vulnerable to forecast error whereas large reservoirs are robust to it. Introduction of inflow forecasts in the planning stage can reduce the unnecessary size of reservoir. Existing reservoirs can function better as if they had virtual capacity expansion and that can also offset the new demands of water supply and reservoir construction.

Keywords: reservoir operation, inflow forecasts, optimization, sustainable reservoir development

1. Introduction

Reservoirs are the most effective means to control water in time and space. According to World Register of Dams(ICOLD,1988), there are 36,235 dams (higher than 15 m) registered in the world. It is roughly estimated that the total amount of reservoir capacities of the world sums up to 18,000 km^3 and the total area inundated is 1,500,000 km^2. As the number of population as well as the water consumption keep on increasing so rapidly, this would certainly create the new demands for water supply in the future. By that time, the existing reservoirs may not be enough to provide sufficient water. Construction of new reservoirs may be needed but it often brings about serious destructive impacts to ecosystems and societies. How to compromise the human needs and the environment is a challenging task that brings us to the principle of sustainable development. We have to meet the needs of current generation without jeopardizing the ability for the next generation to get their needs. For reservoirs, we should make the reservoir development and management in a sustainable manner.

The concrete and workable criteria by which this principle can be applied in practice is yet unidentified. For the time being, the International Commission of Water Resources Systems(ICWRS) has been working out to provide a set of criteria towards achieving this goal. For this aim, some basic criteria of sound and effective management are commonly accepted in principle. Among other means, searching for a new tool is one of the policies (Simonovic, 1994 and COWAR, 1993). Conventional reservoir operation has not taken yet the advantage of recent technological progress such as in inflow forecasts. With the advancement of observation and forecasting techniques, the inflow forecasts may be made with high accuracy in advance.

The objective of this study is to quantify the value of forecast information in multiobjective reservoir operation. Specifically, the value of different levels of forecast accuracy and lead time are evaluated for different reservoir sizes in some given hydrological and socioeconomical conditions. This illustrates the inflow forecasts a powerful tool for sustainable reservoir development and management.

2. Methodology

A basic methodology is to compare the system performance of reservoirs operated under with-and-

* Student Member, Graduate Student, Dept. of Civil and Envi. Engineering, Yamanashi University.
** Member, Professor, Dept. of Civil and Envi. Engineering, Yamanashi University.

without inflow forecast information. The inflow forecasts are explicitly incorporated into the reservoir optimization model using the algorithm that proposed by Takeuchi and Sivaarthitkul (1995) as shown in Figure 1. It consists of two-stage optimization; real-time model and steady state model. The former model is used for the period that the inflow forecasts are available, say L periods. Since the forecasts are considered as deterministic input, the decision of release can be made at the current time t by using deterministic dynamics programming(DDP). This DDP needs boundary conditions that contain the system performances associated with their state variables (storages in this case) at the end of forecast period.

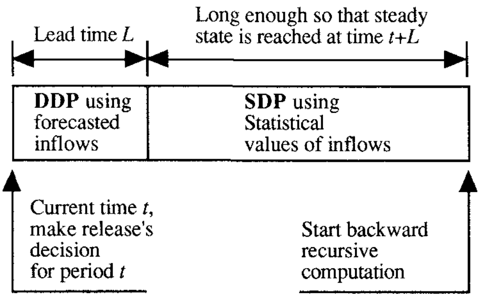


Figure 1 Schematic diagram of optimization algorithm

Such boundary conditions can be obtained from the steady state solution of stochastic dynamic programming(SDP) under periodical first order Markov inflows assumption where the inflow distribution is estimated from the actual realization. The release's decision made during the current time t should not violate the physical constraints, otherwise correction must be made. At the end of the current time t, the storage must be updated using the actual inflow and that release made during time t. The whole procedure is repeated for the next time step and so on until the end of simulation period. This means that when the current time proceeds and new inflow forecasts are issued, optimization has to be made again in the forecast period.

Based on the algorithm mentioned above, the system performance of reservoirs can be evaluated under different levels of forecast accuracy and lead time and then compared with the reference performance that uses no forecasts. The reference performance in this study is obtained from the table policies derived from SDP provided that the current inflow is replaced by historical mean, which is known.

Note that this algorithm can be applied to either maximized or minimized problems. Detailed computations can be found from Sivaarthitkul and Takeuchi, 1995.

3. Synthetic Inflow Forecast Generation

In order to evaluate the value of inflow forecasts under any combination of different forecast accuracy and lead time, the synthetic inflow forecasts need to be generated. This can be achieved by generating the forecast errors and then added to the actual inflow to make the forecast for any lead time of interest. According to Box and Jenkins(1970), the following properties of forecast errors should be maintained; (i) forecast errors should be unbiased; (ii) lead-one forecast error should be uncorrelated; (iii) correlation between forecast errors for longer lead time should be existed; and (iv) variance of forecast error should increase(in the other words, the forecast accuracy should decrease) as the lead time increases. For properties (i) and (iii), the multiseason Markov model can be applied for the forecast errors and can be expressed for l-step ahead forecast as

$$\hat{Q}_t(l) = Q_{t+l} + \rho_{\varepsilon_t}(1)(\hat{Q}_t(l-1) - Q_{t+l-1})\frac{\sigma_{\varepsilon_{t+l}}}{\sigma_{\varepsilon_{t+l-1}}} + \sigma_{\varepsilon_{t+l}}\sqrt{1-\rho^2_{\varepsilon_t}(1)}\cdot e_{t+l} \qquad (1)$$

where $\hat{Q}_t(l)$ is the forecasted inflow for lead-l made at time t; Q_{t+l} is the actual inflow at time $t+l$; $\rho_{\varepsilon_t}(1)$ is the lag-one correlation between forecast errors and assumed constant as 0.8 in this study; $\sigma_{\varepsilon_{t+l}}$ is the standard deviation of forecast error at time $t+l$ (l-step ahead); and e_{t+l} is the random number with zero mean and unit variance and is normally distributed N(0,1). Let us define c_l as a scaling factor, which is expressed as the ratio of standard deviation of the forecast error $\sigma_{\varepsilon_{t+l}}$ to its standard deviation of the actual inflow σ_{t+l}, that is $c_l = \sigma_{\varepsilon_{t+l}} / \sigma_{t+l}$. Equation (1) can then be rewritten as

$$\hat{Q}_t(l) = Q_{t+l} + \rho_{\varepsilon_t}(1)(\hat{Q}_t(l-1) - Q_{t+l-1})\frac{c_l\sigma_{t+l}}{c_l\sigma_{t+l-1}} + c_l\sigma_{t+l}\sqrt{1-\rho^2_{\varepsilon_t}(1)}\cdot e_{t+l} \qquad (2)$$

The forecast accuracy R^2 for l-step ahead is defined as the ratio of explained variance to the variance of actual inflow as

$$R^2 = 1 - \sigma^2_{\varepsilon_{t+l}} / \sigma^2_{t+l} = 1 - c_l^2 \tag{3}$$

where $\sigma^2_{\varepsilon_{t+l}}$ is the variance of forecast error at lead time l; and σ^2_{t+l} is the variance of the actual inflow at time $t+l$. Equation (2) can then generates the synthetic forecasted inflow for lead-l at any forecast accuracy R^2 by simply specifying the value of c_l. If c_l is constant, as performed by Takeuchi and Sivaarthitkul(1995), it implies that the forecast accuracy R^2 is constant for any lead time of forecast. This study assumes that c_l increases linearly with lead time, say by 10 percent, so that R^2 would reduce accordingly for longer lead time. The property (iv) then holds. To generate the uncorrelated lead-one forecast, $\rho_{\varepsilon_t}(1)$ in equation (2) is set to zero so that property (ii) holds.

4. Problem Formulation

A hypothetical system is assumed consisting of two parallel reservoirs as shown in Figure 2. Topographical and hydrological conditions are taken from the two existing reservoirs in the Mae Klong River system in Thailand. Inflows to both reservoirs are assumed to have the basic pattern as same as the existing ones; that is to preserve the historical mean and cross-correlation except the coefficient of variation and lag-one serial-correlation are respectively fixed to 0.3 and 0.8 for the purpose of analyses. This may be viewed as the hydrological condition of tropical Savannah area. The annual mean inflows to reservoir 1 and reservoir 2 are 4,925 and 4,355 million cubic meters (mcm), respectively.

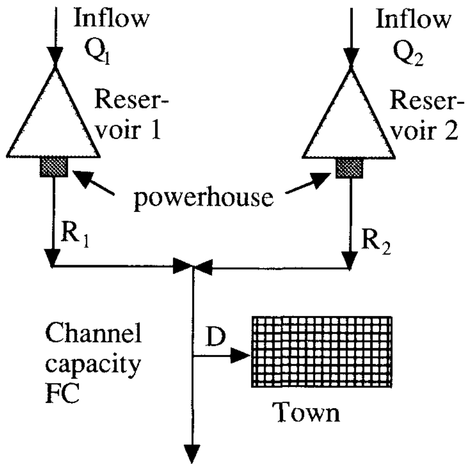


Figure 2 System configuration considered

The objective function is to minimize the losses due to water supply shortage, flood damage; and hydropower shortage. Quadratic loss function is assumed for the first two losses where penalty for water supply shortage is three times greater than the penalty for excess water over the channel capacity of the same amount. Contract level for hydropower generation from both reservoirs is set as 150 MW-month. This selected figure is based on about 60 percent of non-exceeding flow where 50 MW-month is from reservoir 1 and 100 MW-month is from reservoir 2. Note that the average head of the two reservoirs is much different due to the topographic favour. Then the objective function can be defined as

$$\min_{R_{i,t}}\{\beta_1[\max\{(D_t - R_t),0\}]^2 + \beta_2[\max\{(R_t - FC_t),0\}]^2 + \beta_3[\max\{(PTAR_t - \sum_{i=1}^{2} HP_{i,t}),0\}]\} \tag{4}$$

where D_t is the water supply demand at time t; FC_t is the channel capacity limit in mcm/month; R_t is the total releases from reservoir 1 $R_{1,t}$ and reservoir 2 $R_{2,t}$ in mcm/month; $PTAR_t$ is the contract level for hydropower in MW-month/month; $HP_{i,t}$ is respectively the hydropower generation from reservoir 1 and 2 in MW-month/month; β_1 and β_2 are the conversion factors of penalties for water supply shortage and flood damage, respectively; and β_3 is the penalty for power shortage. β_1=0.3, β_2=0.1 and β_3=1000 units/MW-month are used in this study. Note that β_3 is roughly estimated in the sense that loss resulting from halved supply is more or less equal to loss due to power shortage so that the objectives can be competitive.

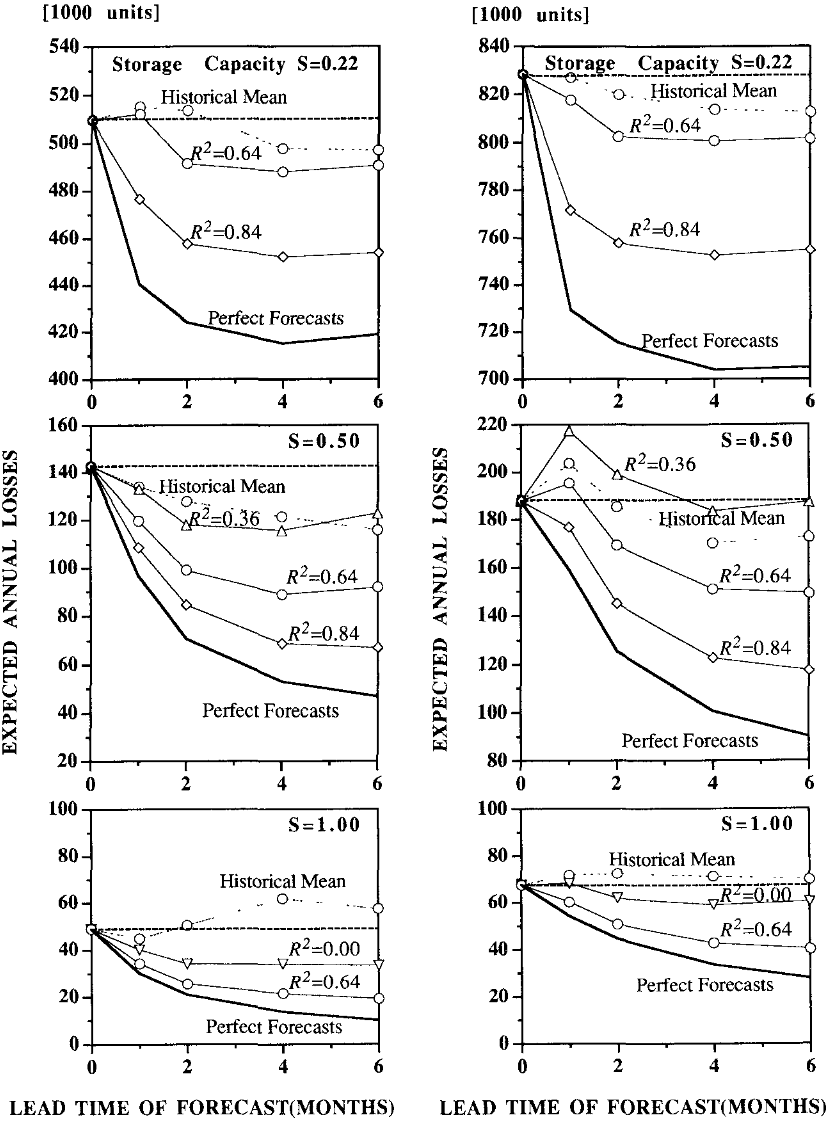
5. Simulation Analyses

Simulations were made using 100-year synthetic monthly inflows as the true realization. The synthetic inflows were made according to the statistical properties required in Section 4. Detailed computation can be found from Takeuchi and Sivaarthitkul(1995). Three different reservoir sizes and two scenarios of water supply were investigated. The size of reservoir is expressed as the ratio of effective capacity to its mean annual inflow and hereafter referred to as storage capacity S, these include S being equal to 0.22, 0.50 and 1.00, respectively. It is essential to note that discretized levels of storage capacity should be made carefully in order that fair comparison of the results could be made(Klemes, 1977). Thus, the discretized levels used in this study for storage capacity 0.22, 0.50 and 1.00 are 5, 10 and 19 levels, respectively. The basic judgement is to keep the increment of storage level the same for any size of reservoir considered. Let us denote D as the ratio of water supply demand to the total annual inflows to both reservoirs. Then the two scenarios of D being equal to 0.48 and 0.96 were used in this study. Combinations of reservoir sizes and water supply scenarios were used for simulation analyses under different forecast accuracy R^2 and lead time of forecast. The simulations were made four times of each 100-year period using different sets of random number in equation (2) in order to avoid the sampling variation of the forecast series. The average of their system performances were adopted and compared with those obtained from the reference performances that employ no inflow forecasts.

6. Results and Discussions

The expected annual losses obtained from the combinations of different forecast accuracy R^2 and lead time of forecast are shown in Figures 3a and 3b where Figure 3a is for demand scenario D=0.48 and Figure 3b is for D=0.96. Each of which is applied to different sizes of reservoir of S=0.22, 0.50 and 1.00, respectively. Lead time-0 is the reference performance without using inflow forecasts. Generally, in any case, the losses decrease when the lead time increases, and reach the minimum at the lead time up to some extent. This may be considered as an optimal lead time beyond which the forecasts have no value or even worse (increasing losses) in case of poor forecasts. The optimal lead time depends also on what accuracy of forecasts is used. For example, the optimal lead time of perfect forecasts for small reservoir (S=0.22) is about 4 months whereas for the larger reservoir, it could not be identified here, since the lead time of forecast in this study is limited to 6 months due to the burden of computer time. If analyses were further made, it might be expected that the optimal lead time for perfect forecasts would be longer for larger reservoir. However, of our interest is the case of imperfect forecasts (R^2<1) in which the optimal lead time within 6 months can be observed in this study. It is revealed that smaller reservoir requires shorter lead time of forecast than that required by larger reservoir. Small reservoir also needs better forecast accuracy as compared with larger reservoir. Considering each reservoir size, in order to obtain the losses being less than the reference performance (without forecasts), the forecast accuracy R^2 required should be better than 0.64 for S=0.22, 0.36 for S=0.50, and 0.00 for S=1.00, respectively. Forecasted by historical mean is also presented in Figures 3a and 3b. This is a naive forecast that requires no forecasting technique rather than the historical knowledge. The purpose is to show that in practice if the forecast accuracy obtained from any forecasting technique performs not better than this level, it should be disregarded.

Figures 4a and 4b compare the losses between the cases of with and without forecasts for different sizes of reservoir. The losses resulting from small reservoir is relatively high and monotonically reduce for larger reservoir. This is because the large reservoir can better manage the imbalance of temporal distributions between demands and supplies (inflows) by utilizing its large space. Gain of forecasts, which is defined as the different between the two performances of with and without forecasts, decreases as the reservoir size increases. It is interesting to note that the implications of value of forecasts in Figures 4a and 4b are very important by at least three aspects. First, in planning stage with a certain acceptable level of losses under a given set of demands (either D=0.48 or D=0.96 in this study), the storage required would be smaller. That means the design of storage capacity can be reduced by incorporating the inflow forecasts. This may be viewed as a new concept for planning stage, which is one of the criteria for sustainable development (COWAR, 1993). Secondly, the existing reservoir can be used more efficiently under a given set of demands, since it can minimize losses as same level as that from larger reservoir that use no inflow forecasts. This is so-called "virtual capacity expansion" as shown in Figures 4a and 4b. The virtual capacity expansion is actually the same size as the reducing capacity in planning stage mentioned before when looking at the problem in the other ways around. And lastly, for real-time reservoir operation it can offset the new demand up to some extent. For instance, suppose there is no forecasts for the existing storage S=0.6 under the current demand D=0.48, a certain level of losses is yielded as shown in Figure 4a. In order to double the demand to D=0.96, the forecast accuracy R^2=0.64 is required for that reservoir to maintain the same level of losses (see the projected line (1) from Figure 4a to Figure 4b). This level of forecast accuracy is not high so that it would not be impossible in practice.



(a) D = 0.48 (b) D = 0.96

Figure 3 Expected annual losses from different levels of forecast accuracy and lead time under different sizes of reservoir and demand scenarios of water supply (a) D=0.48 and (b) D=0.96

It should be kept in mind that the above illustration is based on economical point of view without directly considering the environmental and social impacts. Rather, it is assumed that these two impacts are implicitly, to some extent, expressed in our loss functions. By that sense, our findings from three aspects as discussed above are, certainly, the part of criteria towards obtaining the sustainable reservoir development and management.

7. Conclusions

The acceptable level of forecast accuracy and lead time depends on respective problems of interest. Simulation analyses can be easily performed in the same manner as illustrated in this study in order to evaluate them in quantitative way. From the analyses conducted in this study, the following general conclusions can be drawn:

(1) Small reservoirs are vulnerable to forecast errors. The countries that have small reservoirs need high forecast accuracy and shorter lead time. A haste introduction of low level of forecast accuracy should be cautiously avoided.

(2) Large reservoirs are not so sensitive to forecast errors. In those countries with large reservoirs, a stress should be put to the development of long-term forecasting technique. Even the inflow forecasts of low level accuracy may be useful for large reservoir operation.

As there are tremendous reservoirs in our world, incorporating the inflow forecasts could bring us towards obtaining the sustainable reservoir development and management in the following manner:

(3) It is important in planning stage to take the inflow forecasts into consideration, since it can reduce the necessary storage capacity.
(4) For the existing reservoirs, the inflow forecasts can offset the new demand, to some extent, without expanding their storage capacities.
(5) The existing reservoirs can function better as if they had virtual capacity expansion.

This would reduce a great number of inundated area for the existing and planned reservoirs in the world. As a result, the environmentally and socially destructive impacts would also be reduced.

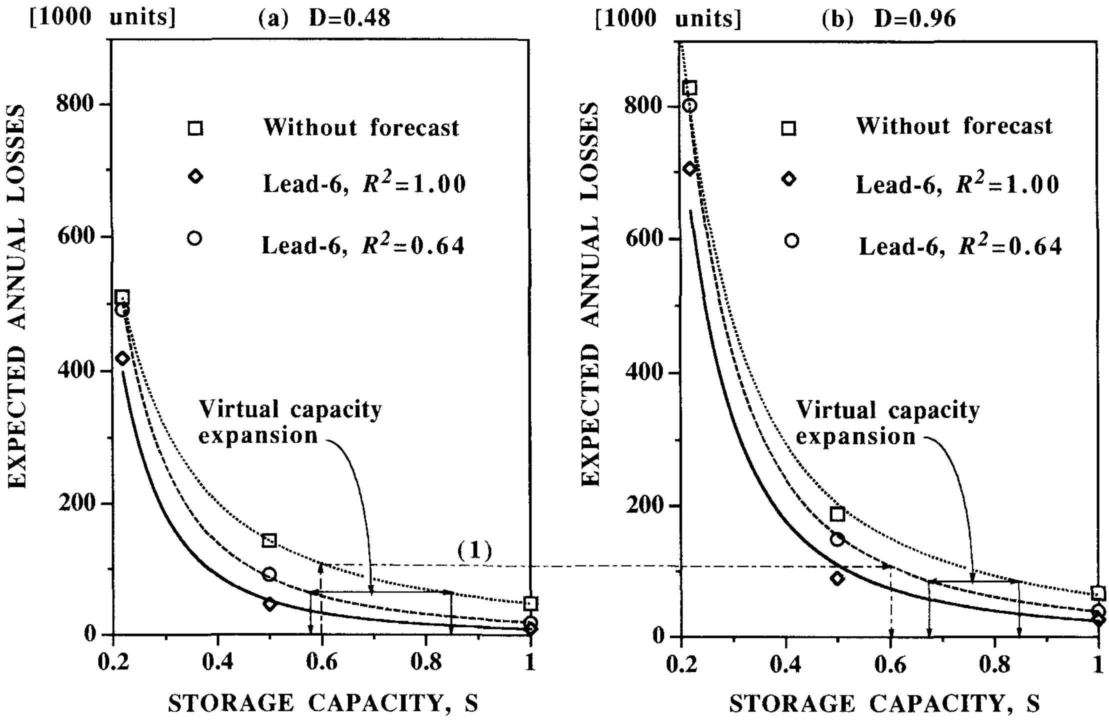


Figure 4 Comparison of expected annual losses from with-and-without using inflow forecasts for different reservoir sizes and demand scenarios of water supply (a) D=0.48 and (b) D=0.96

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