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DERIVATION OF RESERVOIR OPERATING RULES BY IMPLICIT STOCHASTIC OPTIMIZATION

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Implicit Stochastic Optimization is applied to derive monthly reservoir operating rules. The procedure generates synthetic inflow scenarios which are used by an optimization model to find optimal releases. The set of release data are related to storage and inflow in order to form allocation rules. In contrast to the common use of least squares multiple regression to define equations relating releases to the other variables, this papers uses numerical interpolation to calculate the release to be implemented at each period. The methodology is applied to a multipurpose reservoir in Japan and the results highly correlate with those using optimization under perfect forecast.

Key Words: *Implicit Stochastic Optimization, Monte Carlo procedure, reservoir operation*

1. INTRODUCTION

This paper investigates the determination of reservoir operating rules by Implicit Stochastic Optimization (ISO), also known as Monte Carlo Optimization.

The basic principle of the ISO technique is to use a deterministic optimization model to find optimal reservoir releases over an operating horizon assuming a particular sequence of inputs (reservoir inflows). The ensemble of optimal releases is then examined in order to develop a release policy which can be used for practical operation.

The use of Monte Carlo procedures for finding reservoir operating policies was first explored by Young[1)] in a study that utilized dynamic programming applied to annual operations. The optimal releases found by the dynamic programming model were regressed on the current reservoir storage and projected inflows. The regression equation could be thus used to obtain the reservoir release at any time given the present storage and inflow conditions. Karamouz and Houck[2)] extended Young's procedure by adding one extra constraint on the optimization model specifying that the releases must be within a given percentage of the release defined by the previously found operating policy. The releases were again established by least squares multiple regression on the current-period inflow and initial storage. Kim and Heo[3)] used ISO for defining monthly operating rules for a multipurpose reservoir and used two types of linear equations for the regression analysis.

Linear and nonlinear regression is commonly used to find the operating rules from the data obtained by the deterministic optimization model. However, as was pointed out by Willis et al.[4)], examinations of release-storage-inflow relationships often reveal highly nonlinear trends and are not appropriate for simple regression analysis. Willis et al.[4)] devised a different approach that utilized the probability mass function of the optimal releases, conditioned on reservoir storage and inflow.

In this research, such nonlinear trends are also identified and least squares analysis is hence not used. As usual, the optimal releases are related to storage and inflow but the operations are carried out by using numerical interpolation to determine the releases to be implemented. A quadratic optimization model is employed and the procedure is applied to derive monthly operating rules for the multipurpose reservoir that supplies the city of Matsuyama, Japan, which has suffered in the past with problems of scarcity of water. Comparisons are performed against basic simulation techniques and optimization under a perfect forecast scenario.

2. DETERMINISTIC OPTIMIZATION MODEL

It is assumed that the main objective of the operation is to find the allocations of water that best satisfy the respective demands without compromising the system. Another aim is to keep the storage high whenever possible, i.e., every time there exists alternative optimal solutions for the releases. The objective function of the optimization problem can be thus written as follows:

$$\min \sum_{t=1}^{N} \left\{ \left[\frac{R(t)-D(t)}{D(t)} \right]^2 + \left[\frac{S(t)-S_{\max}}{S_{\max}} \right]^2 \right\} \quad (1)$$

where t is the time index; N is the operating horizon; $R(t)$ is the release during period t; $D(t)$ is the demand during period t; $S(t)$ is the reservoir storage at the end of time interval t; and S_{max} is the storage capacity of the reservoir.

Release and storage at each period are related to inflow and spill through the mass balance (continuity) equation for the system,

$$\begin{aligned} S(1) &= S_0 + I(1) - R(1) - Sp(1) \\ S(t) &= S(t-1) + I(t) - R(t) - Sp(t); \quad t = 2,\ldots,N \end{aligned} \quad (2)$$

in which S_0 is the initial reservoir storage; $I(t)$ is the inflow during time t; and $Sp(t)$ is the spill that eventually might occur during time t.

The physical limitations of the system define intervals which release, storage and spill must belong to:

$$0 \le R(t) \le \min[D(t), R_{\max}]; \quad \forall t \quad (3)$$

$$S_{\text{dead}} \le S(t) \le S_{\max}; \quad \forall t \quad (4)$$

$$0 \le Sp(t) \le Sp_{\max}; \quad \forall t \quad (5)$$

where R_{max} is the maximum possible release; S_{dead} is the dead storage; and Sp_{max} is a maximum value attributed to the volume of spillage.

3. MONTE CARLO PROCEDURE AND DERIVATION OF RULES

The steps of the Monte Carlo procedure are as follows:

1) Generate M synthetic N-month sequences of inflow;
2) For each inflow realization, find the optimal releases for all N months by the deterministic optimization model (1)-(5);
3) Use the ensemble of optimal releases (M x N data) to develop operating rules for each month of the year.

In this research the releases obtained by the optimization model, $R(t)$, are related to reservoir storage at the end of the previous time period, $S(t\text{-}1)$, and the inflow during the current time period, $I(t)$. One relationship (rule) is determined for each month of the year. Therefore, with information of initial reservoir storage and forecasted inflow for the current month, the amount of water that should be released can be defined by the particular rule.

The relationships are established by surface graphs which are fitted to the data via numerical interpolation. Thus, the release for any condition of storage and inflow can be found by accessing the correspondent surface. It is to be noticed that no equation is necessary and the allocations are determined only through interpolation.

Like the optimization model (1)-(5) and the ISO algorithm, the surface fitting procedure was constructed in MATLAB and it is based on triangle-based cubic interpolation and Delaunay triangulation.

4. APPLICATION AND RESULTS

The ISO procedure was applied to the Ishitegawa Dam reservoir which supplies the city of Matsuyama, located in Ehime Prefecture, Japan. The reservoir is also used for irrigation and flood control. The maximum reservoir storage (S_{max}) was assumed to be only 8,500,000 m^3, different from the actual capacity of 12,800,000 m^3 because it was desired to observe many shortage situations and then compare how the models handle them.

The Monte Carlo process was run under an operating horizon of 288 months (24 years). 100 sequences of synthetic monthly inflow data were generated by the non-stationary autoregressive model of Thomas-Fiering[5)]. The initial storage was set to S_{max}. The first and last two years of data were rejected to avoid problems with boundary conditions. This provided 24,000 optimal monthly releases.

The data of releases, initial storages and inflows for the months of January through December were grouped and plotted. A mesh of 100 x 100 nodes between the minimum and maximum values of storage and inflow for each month was established and the corresponding values of releases were computed by interpolation generating 12 surfaces, one for each month. **Figs. 1-3** show examples of surfaces generated for January, April and November, respectively. For each surface two boundary conditions were added: minimum storage and minimum inflow implies no release; and maximum storage and maximum inflow implies maximum release. These graphs reveal the high nonlinear correlations among the variables.

After the definition of the release rules, they were applied to a new realization of 24 years of monthly inflows and compared to the results from the utilization of the deterministic optimization model assuming the inflows as perfect forecasts. This new 24-year data set is therefore different from the set used to construct the rules and is utilized in order to verify the usefulness of such rules. In addition, simulations based on the so-called *Standard Linear Operating Policy*[6], or SLOP (**Fig. 4**), were also used for comparison.

Figs. 5 and **6** show results for two different sets of five consecutive years. Comparing the results from the optimization under perfectly forecasted inflows with the ones from the SLOP it can be noticed that the optimization model tries to mitigate the great concentrated deficits that happen with the SLOP by decreasing the releases prior to shortage periods so that the overall deficit also diminishes. It is also observed that the simulations using the ISO-generated rules try to allocate water in a way very similar to the optimization (**Fig. 7**). In fact, the correlation coefficients regarding water allocation between the results obtained by the release rules and optimization under perfect forecast were 0.85 and 0.90, for both 5-year sequences, respectively. The correlations of the SLOP with optimization for both 5-year sequences were only 0.73 and 0.66, respectively.

This shows that the results from the derived release policies were quite satisfactory given the fact they have information only on the previous reservoir storage and current inflow whereas the optimization model has knowledge of inflows for the whole operating horizon and thus better means to define superior policies.

The authors believe that improved release rules and therefore operating policies may have been found if more years had been used for the Monte Carlo procedure. Due to computer storage, however, this was not attempted in the current research. Nevertheless, the results were promising.

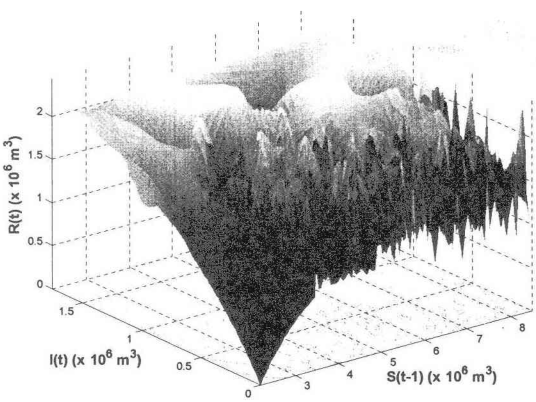


Fig. 1 ISO-generated rule for January.

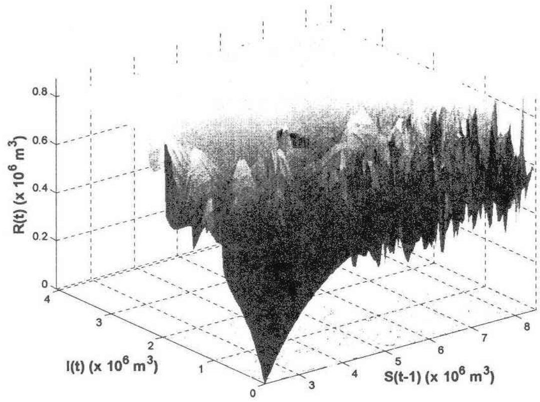


Fig. 3 ISO-generated rule for November.

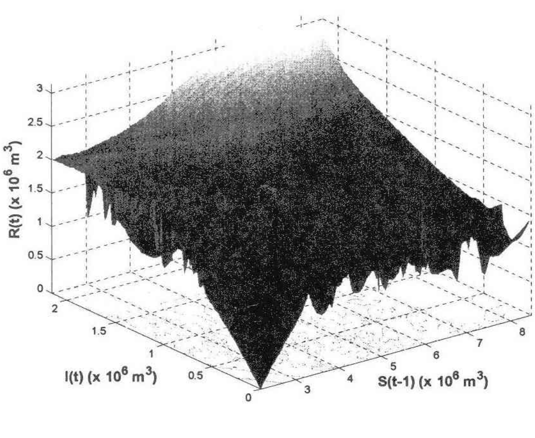


Fig. 2 ISO-generated rule for April.

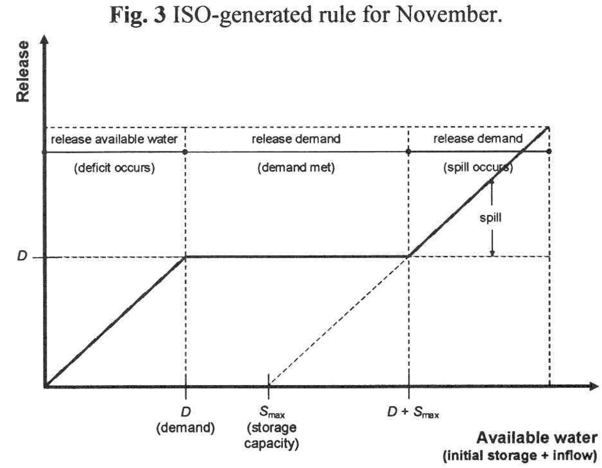


Fig. 4 Standard Linear Operating Policy.

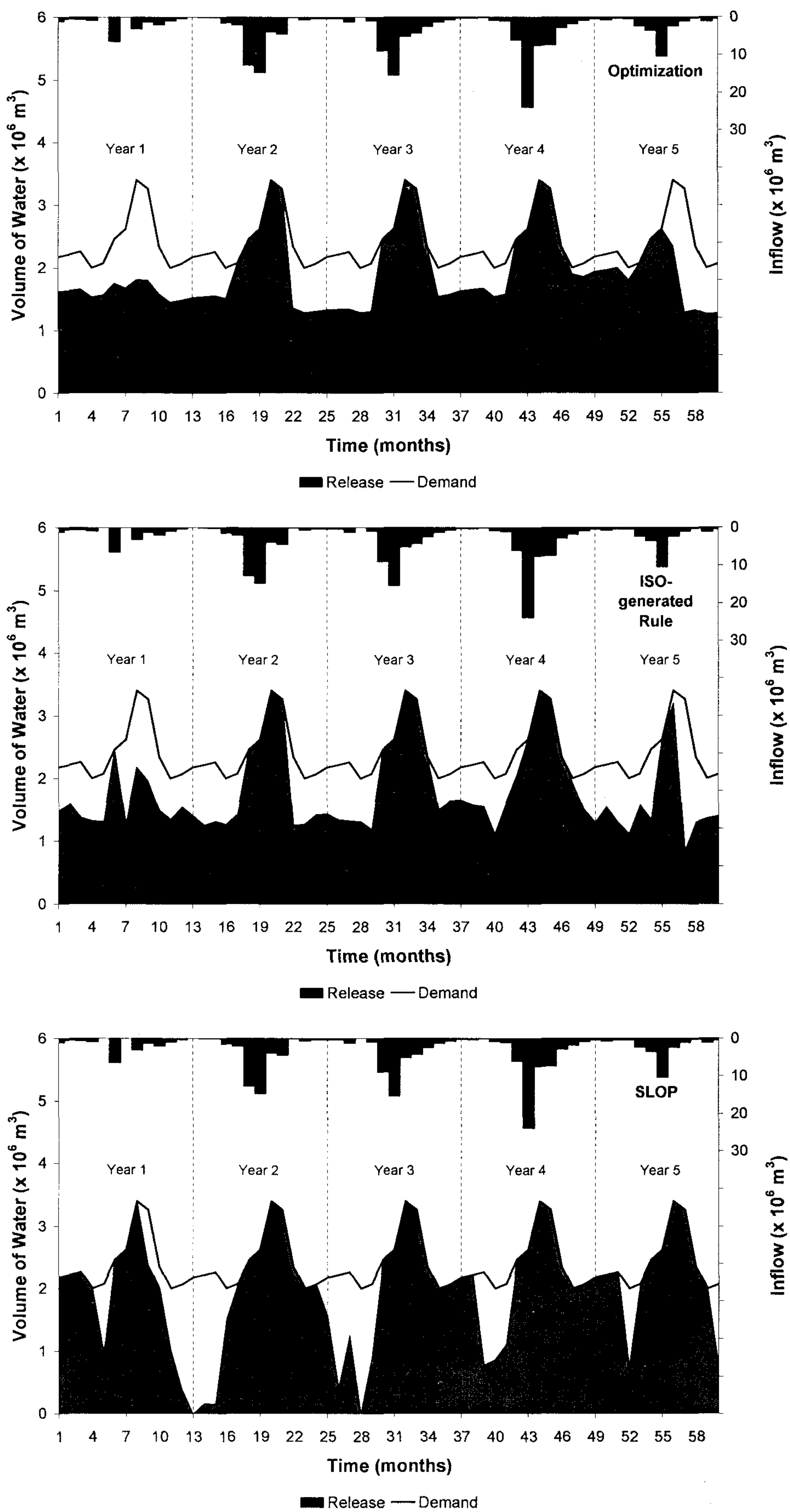


Fig. 5 Results for the first set of five years.

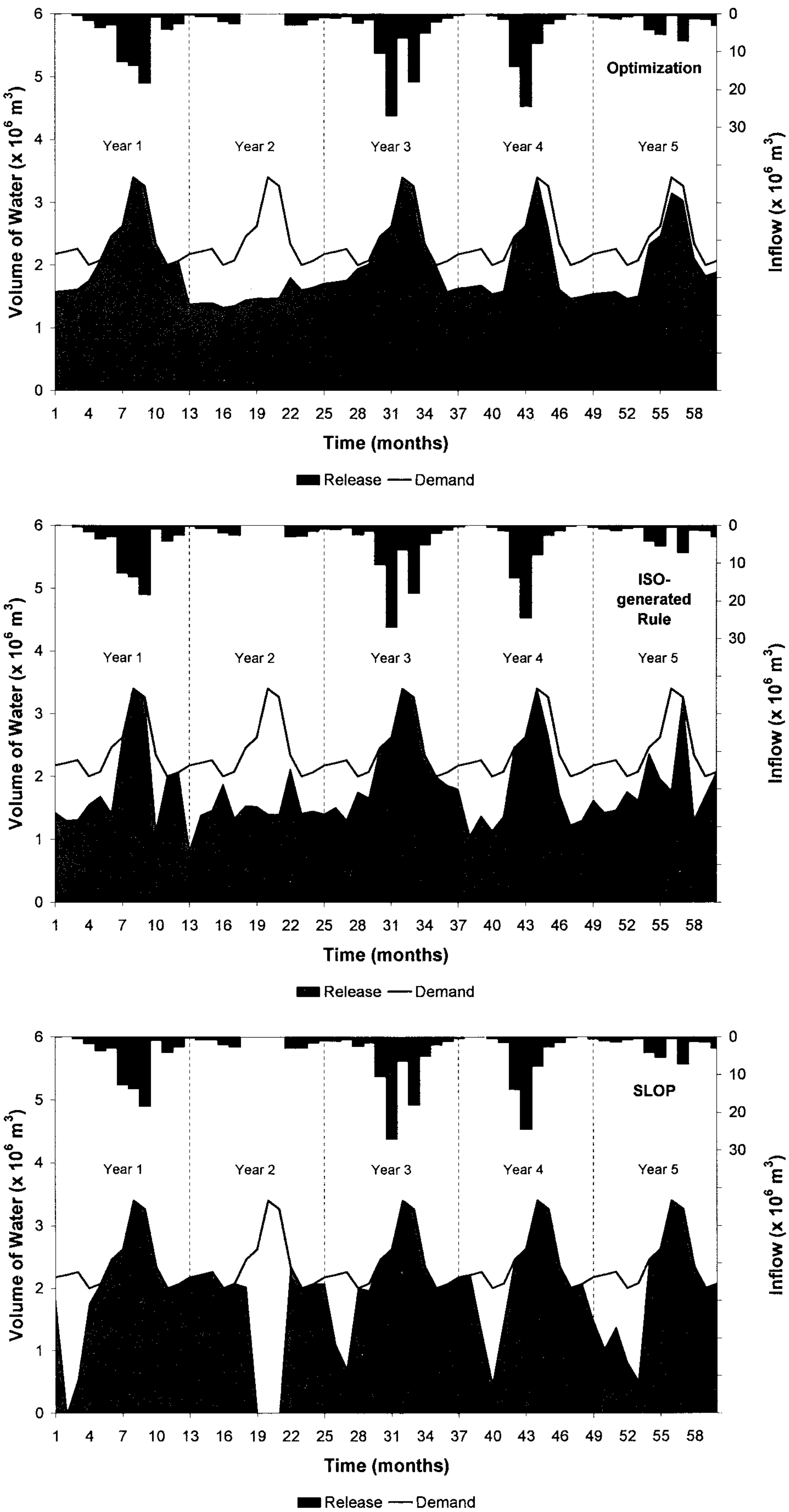
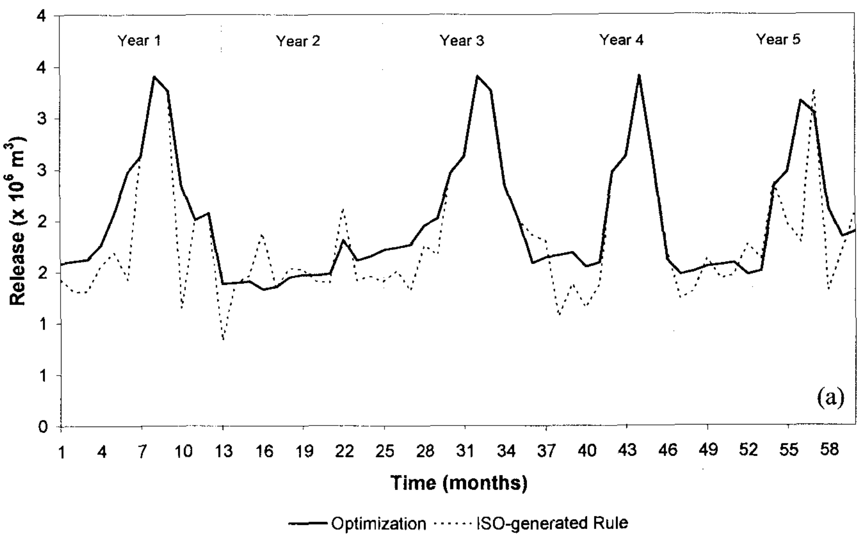


Fig. 6 Results for the second set of five years.



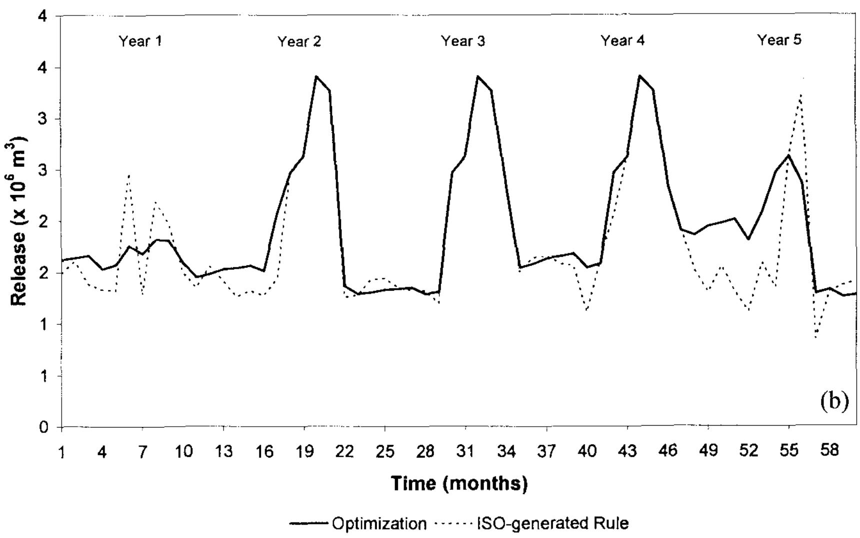


Fig. 7 Correlations of releases obtained by optimization and ISO-generated rules for the (a) first and (b) second 5-year set.

5. CONCLUSIONS

In this study, Implicit Stochastic Optimization was applied to define monthly operating rules for a multipurpose reservoir. The procedure solved a number of quadratic deterministic optimization models each of which with a given realization of reservoir inflows and then used the generated data to construct release-storage-inflow relationships for every month. These relationships were afterward utilized as a basis to simulate new operations and showed able to produce policies relatively identical to the ones found by optimization alone.

Such procedure may be thus useful as screening tolls in the decision-making process of reservoir operation.

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