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THE MANAGEMENT OF LAKE COMO

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PREFACE

Analysis of problems concerned with the rational use of natural resources almost invariably deals with uncertainties with regard to the future behavior of the system in question and with multiple objectives reflecting conflicting goals of the users of the resource. Although effective mathematical tools have been made available during the last decades for solving such problems, there have only been few applications, even in the field of water resources, which is certainly the most developed one. The major reason for this is probably due to the fact that such mathematical tools are often quite abstract and sophisticated and are therefore of little help for the practitioners.

For these reasons, one of the issues addressed during the summer study "Real-time Forecast versus Real-time Management of Hydrosystems" organized by the Resources and Environment Area of IIASA in 1981, was the possibility of developing simple and heuristic methods for reservoir management that could directly take into account the experience and the preferences of the manager. The research was mainly conducted with reference to the case of Lake Como, for which substantial data were available. This paper is one of a short series of IIASA publications based upon the results obtained during the study. It describes the philosophy of the approach, the most important results, and the practical impact they recently had.

Janusz Kindler
Chairman
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ABSTRACT

This paper presents a new and heuristic approach for improving the performance of multipurpose reservoirs already in operation. The main characteristic of the method is that the analyst must first learn from the past experience of the manager and synthesize it into a very simple operating rule. Then, the analyst must point out with the help of the manager what the acceptable modifications of such a rule are. Only after these phases have been carried out can possible improvements in the management be obtained by using standard optimization techniques.

The method has been applied to the case of Lake Como, (Northern Italy), and the results are quite satisfactory since the major objectives of the management can be substantially improved. The average duration of the floods on the lake shores and the mean volume of the water deficits in the downstream agricultural areas are about halved, without lowering the mean yearly electricity production of the downstream run-of-river plants. Moreover, the advantages of a revision of the active storage and of a possible protection of the shores of the town of Como are also investigated.

All the results of this study had a direct impact on the management of the lake. In fact, the proposed operating rule has been programmed on a microcomputer, which is now used every day by the manager as an essential support for his final decision; the active storage was lowered in June 1982 by the Ministry of Public Works, and the sunken part of Como town will be soon repaved and elevated by the Municipality.

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THE MANAGEMENT OF LAKE COMO

1. INTRODUCTION

The Adda river, flowing out of Lake Como in Northern Italy (see Figure 1), has been used to irrigate the Padana plain since Roman times. At the end of the nineteenth century, hydroelectric power stations were developed along the course of the river to supply the growing needs of the city of Milan. During World War II, the lake was transformed into a reservoir by constructing a regulation dam at Olginate. Constraints on its operation were imposed by a formal act of the Ministry of Public Works, which assigned the regulation license and defined the active storage of the lake. Since then, most of the uses of the Adda water have remained unchanged, but they still contribute to a significant portion of the Italian GNP.

In recent years, the problem of the operation of the dam has become increasingly critical for the greater damages generated by the floods on the lake shores, particularly in the town of Como. In fact, the main square of Como and the surrounding area (probably because of overpumping from the underground aquifer) have been progressively sinking since the beginning of the sixties, thus substantially increasing the risk of flood during periods of high inflows. Since the road along the lake

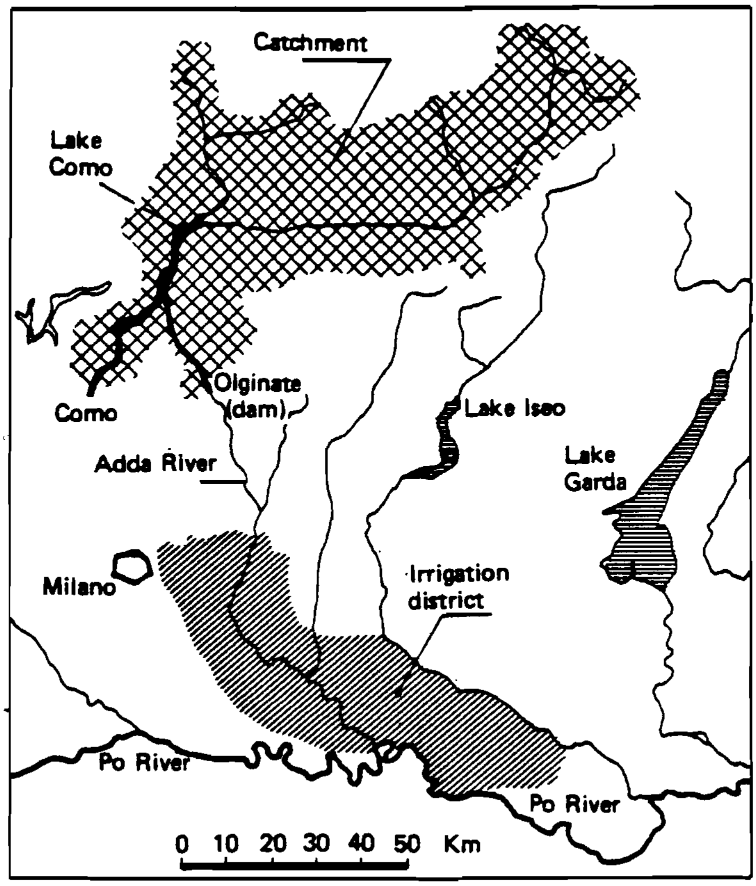


Figure 1. Lake Como basin and irrigation districts.

links the eastern and western part of Como and the square is the heart of the commercial life of the town, its effective protection from floods has been the subject of an intense debate between the agency responsible for the lake management (Consorzio dell'Adda) and the municipality of Como.

This paper reviews the effectiveness of some proposed solutions: the first is merely a modification of the actual operating rule, the second is a revision of the active storage, and the third is the repaving and elevation of the sunken part of the town. More precisely, the next section analyzes the physical endowment of the lake and relative catchment, together with the main objectives of the management. In Section 3, the characteristics of the operating rule implicitly used by the lake manager during the period from 1946-1980 are extracted from the historical data and interpreted in terms of the management objectives. In Section 4, the management problem is formulated and solved as a multi-objective mathematical programming problem, taking explicitly into account the past experience of the manager. In the following section, a particular operating rule is selected within the set of efficient operating rules and analyzed in detail in order to better estimate the improvements generated by this rule if it were to be applied in the future. In Section 6, the impact of a possible reduction of the active storage on floods and agricultural production is discussed, and a similar analysis is performed in Section 7 to evaluate the opportunity of protecting the sunken part of the town (Como square) from floods. Finally, the last section summarizes the results and their practical implications, and then discusses the advantages of the methodology used in the paper, which should be of general interest to other lake managers.

2. MAIN OBJECTIVES OF LAKE COMO MANAGEMENT

Lake Como receives water from a catchment of 4 508 km^2, at a mean elevation of 1 500 m in the central part of the Alps, (see Figure 1). The outflow rate of the lake can be varied from day to day by a "manager" (actually a committee) who has the responsibility of operating the dam at Olginate. The inflow rate averages 160 m^3/sec and has the typical annual pattern of alpine rivers with two peak flow periods, one in early summer due to the snow melt, and another in autumn due to rainfall. This natural pattern of inflows has been altered somewhat by upstream hydro-electric reservoirs mostly built during the period from 1957-1964. This increased the storage capacity upstream of the lake from 208 million cubic meters in 1957 to more than 500 million cubic meters in 1964, and induced a marked shift in the monthly means of the inflows, since hydro-electric reservoirs retain a portion of the summer runoff in order to supply peak power to the national network during winter. For example, the average inflow in December has increased by 17% (16 m^3/sec). Thus, only the periods 1946-1956 and 1965-1981 can be assumed to have stationary characteristics of inflows. A second significant change in lake management has been caused by the sinking of Como square by some 60 cm, mostly during the period from 1966-1973. Both these facts have obviously influenced the lake manager, so that only in the periods from 1946-1956 and from 1977-1980 can the operation of the dam be considered as stationary.

Water from Lake Como supplies a group of downstream users before reaching the Po river, some 140 km south of the lake. More precisely, 6 agricultural districts and 7 run-of-river hydro-electric power plants are located along the course of the Adda river and are served by the network of canals sketched in Figure 2. The main crops are corn, wheat, and forage, and the irrigated surface totals about 144 000 hectares. The installed capacity of the power stations is about 92 MW for an annual mean production of 473 GWh, which is about 58% of the maximum producible energy. The production functions of all these users are not well-known and economic data on agriculture are scarce and quite unreliable. It was therefore natural to characterize the performance of the lake operation by means of simple physical indicators affecting the costs and benefits of all parties involved. In particular, for irrigated districts, a good indicator

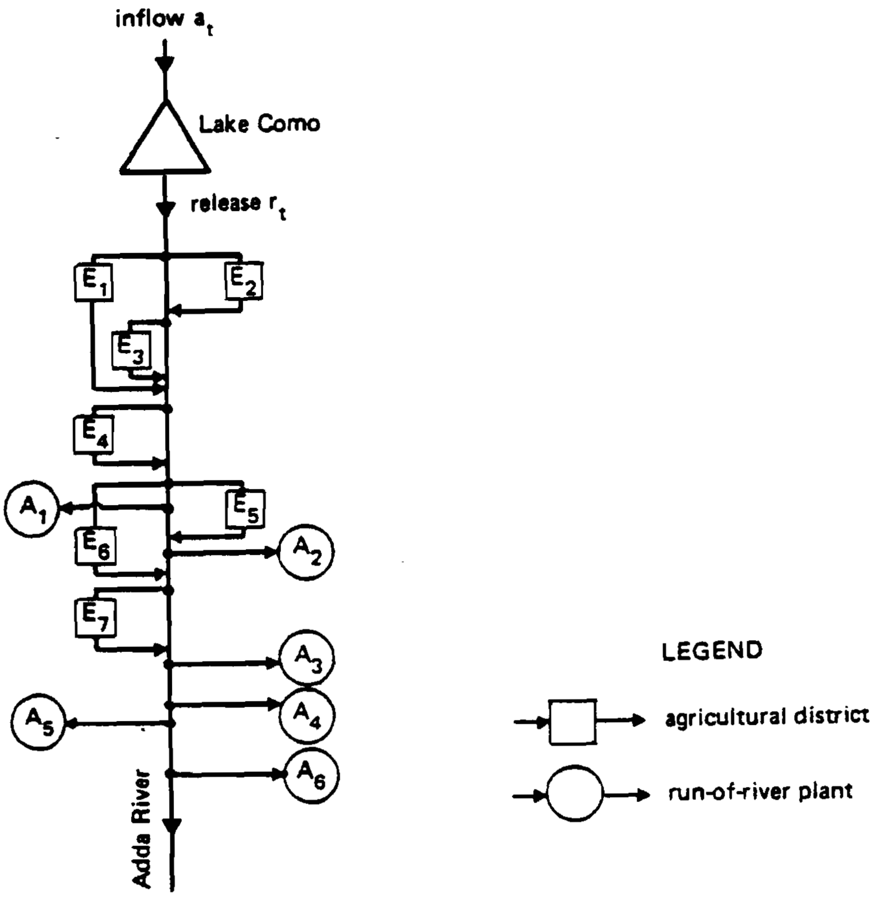


Figure 2. Downstream distribution network (A_i = agricultural district; E_i = hydropower station).

was considered to be the volume of water deficit evaluated with respect to the nominal requirements, again fixed by a document of the Ministry of Public Works. For hydro-electric power stations, the difference between the maximum usable flow and the flow actually available to the power plants has been used. Thus, for each day t the water deficit d_t^i of each user i, (i=1,...,6 for agricultural districts, and i=7,...,13 for hydro-electric power stations) is defined as

$$d_t^i = \begin{cases} 0 & \text{if } q_t^i \geq w_t^i \\ w_t^i - q_t^i & \text{if } q_t^i < w_t^i \end{cases}$$

where q_t^i is the flow rate actually delivered to user i in day t, and w_t^i is the corresponding nominal agricultural requirement or the maximum usable flow in each power station (for these users, the loss of energy can be easily computed because the hydraulic head h^i, i=7,...,13 of the turbines is known). Finally, the objectives of the downstream users were assumed to be the minimization of the expected value A of the total annual deficit in the agricultural sector expressed in 10^6m , and the minimization of the expected value E of the annual hydro-electric power loss in GWh, i.e.,

$$A = E\left[\sum_{1}^{365}{}_t \; \sum_{1}^{6}{}_i \; d_t^i\right]$$

$$E = E\left[\sum_{1}^{365}{}_t \; \sum_{7}^{13}{}_i \; kh^i \; d_t^i\right]$$

where E[·] represents the expected value and k is a suitable unit conversion factor.

As for Como town, the damage suffered from floods can be characterized in several ways. Two of the most common indicators are the peak level of the flood and the duration of the flood. The former seems to be more representative of the direct damages, while the latter can more precisely characterize the damages due to interruption of productive activities. Total damages should therefore be evaluated by a suitable weighted mean of these two factors. A simple statistical analysis of the duration and peak of all the floods that occurred during the period from 1946-1980 has shown, however, that these two indicators are highly correlated ($\rho=0.97$), so that the total damages can be reasonably characterized by only one of these factors. The choice has been to consider the minimization of the expected number F of days of flood per year, (which has been about 8.5 in the last 20 years), as the objective of Como town.

Other objectives were considered to be of minor importance and already satisfied, at least to a certain extent, by the constraints imposed on the operation of the dam: for example, navigation on the lake is guaranteed by dead storage, while sudden propagation of flood waves downstream is prevented by a limit imposed on the rate of variation of the release from the dam.

3. ANALYSIS OF THE PAST MANAGEMENT

The license act, which gives the Consorzio dell'Adda the right to operate the dam at Olginate, specifies that the manager can freely decide the release r_t of each day t, whenever the lake level x_t at the beginning of the day falls at a specified interval $(\underline{x}, \overline{x})$, constant all over the year, and from now on called control range. This control range measured relative to the elevation of the Malgrate hydrometer, is -0.50 m, 1.30 m, which corresponds to an active storage of about 250 million cubic meters. When the level x_t of the lake equals the lower limit $\underline{x}$, the manager must release a flow rate equal to or lower than the inflow, so that the level cannot drop below $\underline{x}$. On the other hand, when the level reaches or exceeds the upper limit $\overline{x}$ of the control range, the manager must progressively open all the gates of the dam in order to discharge as much as possible, thus avoiding too much flooding on the lake shores. In other words, when $x_t > \overline{x}$, there is no freedom for the manager in making the decision and $r_t = L(x_t)$, where L represents the so-called stage-discharge function of the lake (see Figure 3).

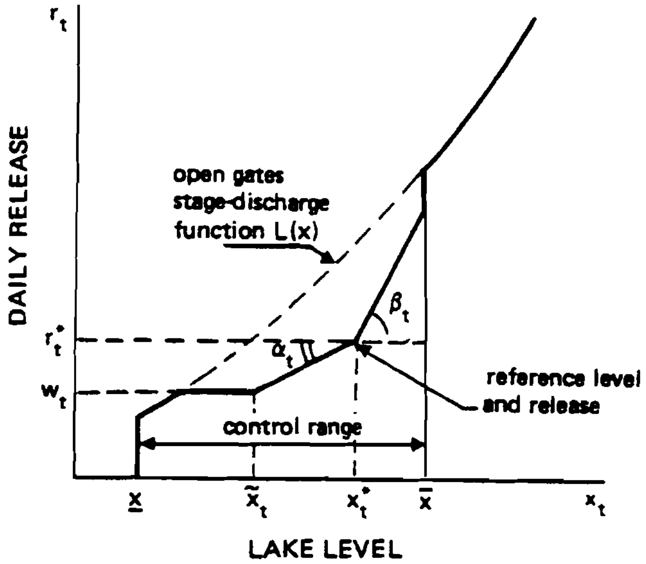


Figure 3. The operating rule of Lake Como.

This function gives, for any value of the level x_t, the maximum amount of water which can be released in one day by keeping all the gates of the dam permanently open.

The manager's release in the control range was not specified in the license act and is thus mostly based on past experience. In practice, it can be reasonably assumed that the release r_t of each day t of the year mainly depends upon the amount of available resource, i.e.,

$$r_t = r(x_t, t) \quad .$$

Of course, such an operating rule must be periodic with respect to t because of the yearly periodicity of inflows and water requirements. Moreover, in standard hydrological conditions, the manager follows a precise schedule of releases r^*_t from which he deviates whenever the level differs from a reference value x^*_t (rule curve). This deviation Δr_t can be considered proportional, through two coefficients α_t and β_t, to the lack or excess of resource, that is (see Figure 3)

$$\Delta r_t = \begin{cases} \alpha_t (x_t - x^*_t) & \text{if } \tilde{x}_t < x_t < x^*_t \\ \beta_t (x_t - x^*_t) & \text{if } x^*_t < x_t < \bar{x} \end{cases}$$

where $\tilde{x}_t$ is implicitly defined as the level x_t at which the release $r_t = r^*_t - \alpha_t(x^*_t - x_t)$ equals the total agricultural requirement w_t of day t ($w_t = \sum_{i=1}^{6} w^i_t$). Furthermore, when $x_t < \tilde{x}_t$, the release is set equal to w_t or to the maximum feasible release $L(x_t)$. In conclusion, the manager can be considered to behave in any day t of the year according to the operating rule depicted in Figure 3. Thus, the control range is subdivided into three zones. In the lowest one (namely for $\underline{x} < x_t < \tilde{x}_t$) the target of the manager is simply to satisfy agricultural requirement. In the second zone ($\tilde{x}_t < x_t < x^*_t$) demand for electricity production is also considered, while in the last zone ($x^*_t < x_t < \bar{x}$ flood protection becomes the dominant objective.

The values of the parameters α_t and β_t, in the following called α_t^* and β_t^*, have been estimated by minimizing the sum of squares of the differences between historical values of the releases and the values which would have been generated by a systematic application of the operating rule shown in Figure 3. This identification of the operating rule was performed separately for the two periods during which the basin characteristics were stationary. Sample results of this identification are shown in Figure 4. The upper line represents the values of β_t identified for the period from 1977-1980, while the lower line refers to the period from 1946-1956. Since the parameter β_t represents in a way the sensitivity of the manager to the risk of flood, it is not surprising that the pattern of the two curves is similar and strongly correlated to the pattern of inflows (see Rinaldi 1982) with peaks during periods of high inflows. The sinking of Como square has, however, led the manager to substantially increase his sensitivity to floods, (i.e., the values of β_t^*) particularly during the snow melting season. As for the parameters α_t^*, they do not exhibit significant seasonal fluctuations neither do they seem to be affected by the sinking of Como. Furthermore, it turned out that $\beta_t^* > \alpha_t^* > 0$ for all t, which explicitly quantifies the intuition that the operating rule is increasing and convex with respect to storage.

The correlation between actual and simulated releases is 0.96 for the period from 1946-1956, and 0.98 for the period from 1977-1980; the standard deviation of the difference between actual and simulated releases is only 19% of the mean release in 1946-1956 and 15% in the last period. Finally, the levels that would have been generated by using the identified operating rule are also highly correlated to the historical ones. Thus, it is possible to conclude that the identified operating rule interprets the past data fairly well and captures most of the operational characteristics of the manager.

4. EFFICIENT OPERATING RULES

Following an approach outlined by Zielinski et al., (1981), possible improvements of Lake Como management were considered

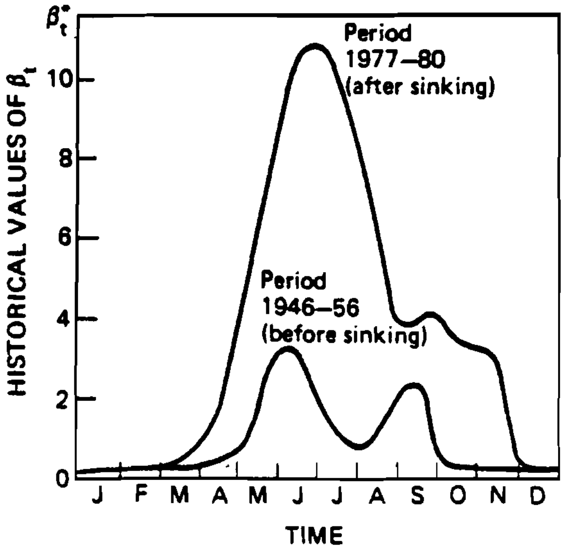


Figure 4. Values of β_t^* in two different periods.

which only imply acceptable perturbations of the past operating rule. According to the manager's recommendations, the values of the parameters α_t and β_t were considered to be modifiable, provided that their seasonal variations were preserved. Consistently, the operating rules from which the optimum was searched are still of the type shown in Figure 3, but with

$$\alpha_t = a\alpha_t^*, \qquad \beta_t = b\beta_t^*, \qquad t = 1,\ldots,365 \quad ,$$

where a and b are two unknown constant parameters to be determined through optimization, and α_t^* and β_t^* are the values estimated for the period 1977-1980.

Thus, the stochastic multiobjective programme that allows the determination of the <u>efficient operating rules</u> (see, for example, Cohon and Marks 1975), can be formulated in the following way

$$\min_{\{a,b\}} \quad [A \quad E \quad F] \quad , \tag{1}$$

(see Section 2 for the definition of A, E, and F), subject to a set of mass balance equations representing the network of canals downstream of the lake and the actual rules of distribution among the users, and to the continuity equation

$$x_{t+1} = x_t + a_t - r(x_t, t, a, b) \qquad t = 1,2,\ldots \tag{2}$$

where the inflow a_t is a one-year cyclostationary stochastic process and $r(x_t, t, a, b)$ is the family of operating rules considered as candidates for optimality. As is well-known, the solution of the above problem is not unique, but is represented by a set of efficient operating rules. Each one of them is identified by a particular pair (a^o, b^o) of parameters and has the property that any variation of such parameters weaken at least one of the three objectives of the problem.

This set of efficient operating rules (i.e., the set of pairs (a^o, b^o)) has been determined by simulating the daily behavior of the system in a series of years (1965-1979) for various pairs (a, b) of the parameters, thus estimating the corresponding values of the objectives (in such simulations the level of Como square was fixed at its present value). The efficient solution can be represented by a line in the two-dimensional space of the parameters (a, b) or by a surface in the three-dimensional space (A, E, F) of the objectives. In Figure 5, such a surface is represented by the contour lines with E = constant. In the same figure, point H represents the "historical values" of the objectives, namely the values that would have been obtained under nominal conditions by systematically applying the operating rule with a = b = 1 (i.e., the operating rule identified in the preceding section); while the utopia point U represents the (independent, and hence infeasible) absolute minima of A and F.

The analysis of Figure 5 allows several interesting considerations. First, hydro-electric power production is much less sensitive to the parameters (a^o, b^o) than the other two objectives. The range of variation of E among all efficient solutions is indeed only 22% of the absolute minimum, while A or F can vary 6 and 50 times, respectively. Figure 5 shows also that marginal reductions of hydropower deficit below the historical value (equal to 195 GWh) entail a severe sacrifice in terms of agriculture and flood protection. Moreover, for relatively high values of E (for example, E = 200 GWh), the number of days of flood is quite insensitive to the agricultural deficit, provided the last is greater than 80 million cubic meters, while a slight decrease of A below this value leads to a sudden and very sharp increase in the number of days of flood. On the other hand, for lower values of E (say 192 GWh) the relationship between agricultural deficits and flood protection is much more "smooth". Finally, it is worthwhile noticing that the past management of the system can be improved by adopting any operating rule corresponding to points within the curvilinear triangle BHD. Selecting, for example, a point like P in Figure 5, maintains the hydropower deficit at its historical value and decreases the mean number of days of flood from 10.2 to 6.3 and the average agricultural deficit from 201 to about 98 million cubic meters (see next section for more details).

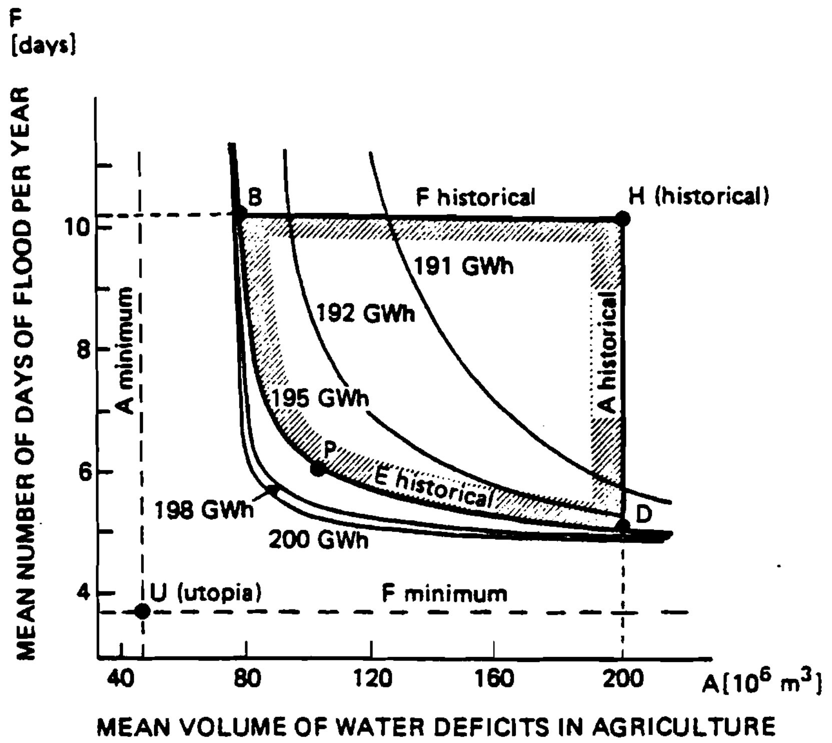


Figure 5. Efficient solutions in the space of the objectives.

The first reduction is mainly due to an increase in the sensitivity to floods ($b^o = 2.1$), which, during the period of high inflows, would force the manager to completely open the dam even if the level of the lake is 30 or 40 cm below the upper limit $\overline{x}$ of the control range. On the contrary, the reduction of the agricultural deficit is certainly due to a more intensive use of the lower part of the active storage, thus indicating that in the past, the manager's attitude with regard to droughts has certainly been more risk-adverse than what is suggested by the present stochastic approach (for a detailed investigation of this point, see Guariso et al., 1982).

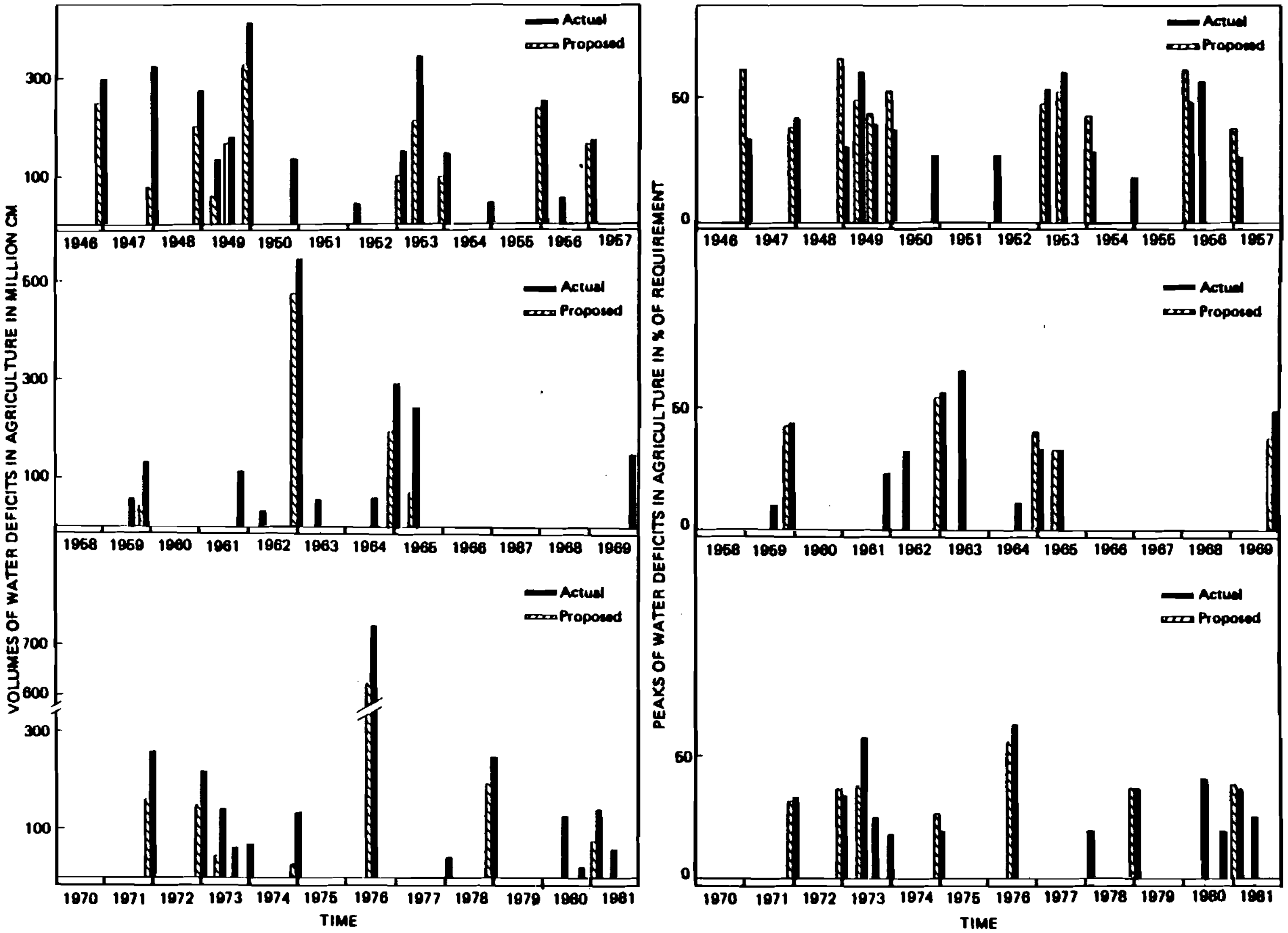
5. ANALYSIS OF A PARTICULAR OPERATING RULE

Before implementing any particular efficient operating rule, one must perform a detailed and careful analysis in order to test its reliability. In particular, any proposal of modification of the actual operating rule, besides giving advantages in terms of the yearly averages of the objectives, should also be proved to be superior during the most significant and critical episodes. Moreover, the advantages with respect to the past must be clearly detectable for any reasonable sequence of inflows and not only for the data set used for optimization (see preceding section). Finally, it is worthwhile checking whether some minor objectives that were neglected in the optimization phase are satisfied, at least as much as in the past.

In our case, the series of daily releases and storages obtained by using the efficient operating rule corresponding to point P of Figure 5 for the whole period from 1946-1981 was presented to the manager and thoroughly discussed with him. The selection of this efficient operating rule is obviously due to the "shape" of the efficient set: in particular, point P in Figure 5 is on the intersection of the contour line characterized by historical hydro-electric power deficit (E = 195 GWh) with the segment HU, so that the surplus of benefit is divided between agriculture and flood protection in proportion to their maximum obtainable surplus of benefits. The main objection raised by the manager to this proposed solution was that the storage was too frequently at its minimum allowable value during the dry season. Indeed, when $x_t = \underline{x}$, the release r_t must be equal to (or smaller than) the inflow a_t, and therefore, in such conditions, the release can fluctuate quite substantially from day to day, thus generating a certain number of inconveniences to downstream users. In order to avoid such a problem, the operating rule was slightly modified by progressively reducing the release in the lowest part of the control range. This marginally increased the values of A and E, but provided a much more satisfactory pattern of releases.

Finally, a detailed analysis was performed in order to compare the proposed operating rule with the actual one for the whole period of operation (1946-1981). In particular, historical droughts and floods were directly compared with those produced by the proposed operating rule, and the comparison was carried out in terms of "peak", "duration", and "volume" for the deficits, and in terms of "peak" and "duration" for the floods. Two problems had to be solved in order to provide a realistic comparison. The sinking of Como was simply accounted for by using the estimated values of β_t^* during the periods from 1946-1956 and from 1977-1980 (see Figure 4) and a linear interpolation between these values during the period from 1957-1976 (this means that the coefficients β_t of the proposed operating rule were forced to be always about the same proportion of the historical coefficients). The second problem was much more complex since data on the actual agricultural water demand were not registered in the past. The analysis was thus again based on the nominal requirement w_t, but comparing only those droughts that were classified as severe or relatively severe by the manager.

Figures 6 and 7 illustrate the results of this analysis. The volume of all deficits generated by the proposed operating rule is lower than the corresponding historical value (see Figure 6a). The same is true for the duration of the deficit (which is not reported in the figure), while in a few episodes the peak daily deficit generated by the proposed operating rule would have been slightly greater than



(a) (b)

Figure 6. Deficit volumes (a) and peaks (b) in the period from 1946-1981 corresponding to the actual management (black) and to the proposed operating rule (dashed).

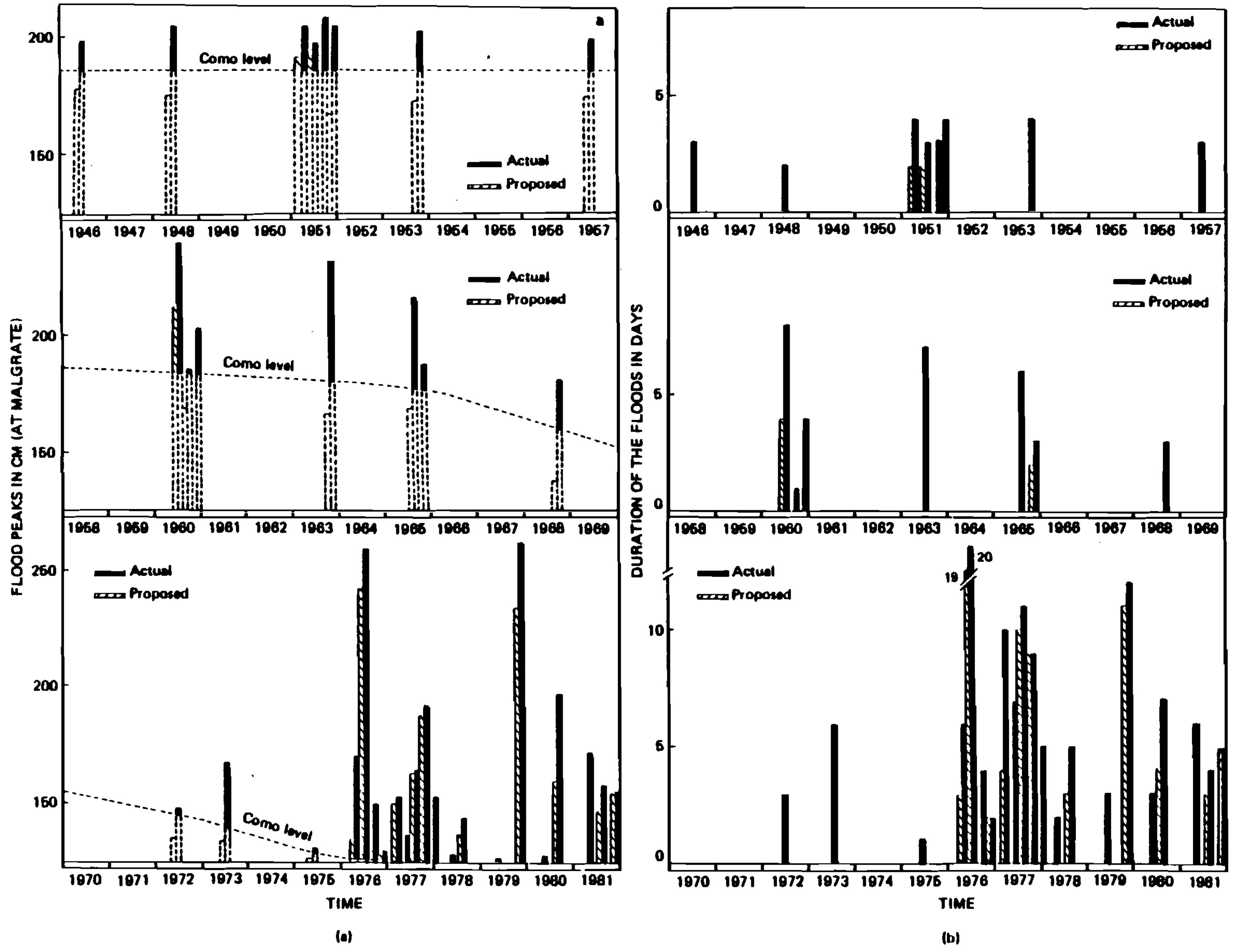


Figure 7. Flood peaks (a) and durations (b) in the period from 1946-1981 corresponding to the actual management (black) and to the proposed operating rule (dashed).

the historical one (see Figure 6b). This happens however, mainly in winter and in the period from 1946-1956, namely before the construction of the alpine reservoirs, when the seasonal variations of the inflows were quite different from those of the period from 1965-1979 on which the optimization was performed. As far as floods are concerned, the proposed operating rule would have generated lower peaks (Figure 7a) and shorter floods (Figure 7b) in all the 36 episodes historically recorded.

A simple statistical analysis (based on Student distribution) shows that one can be practically sure that the proposed operating rule is better than the actual one. In fact, the 99% confidence intervals of the mean ratio between proposed and historical indicators of droughts and floods are the following:

deficit volume : 0.32 ± 0.17
deficit duration : 0.26 ± 0.15
deficit peak : 0.69 ± 0.27
flood duration : 0.30 ± 0.16
flood peak : 0.87 ± 0.03

Hydro-electric power deficits cannot be split into separate episodes, since power stations only rarely operate at maximum production. These deficits were thus divided into two seasons: summer (April-September), and winter. The mean value of the winter production obtained by using the proposed operating rule was about 8 GWh less than the historical one, while the summer production was about 5 GWh higher. This means that the use of such a rule would have implied a mean annual loss of potential hydro-electric power of just 0.3% with a shift of about 0.6% from winter to summer (a fact which is again partly due to the construction of the upstream reservoirs).

The use of the operating rule discussed in this section was formally suggested to the manager in Spring 1981, while later in 1982, the rule was programmed on a microcomputer, (IBEX 7100) which has since been used by the manager. Sometimes the manager deviates from the suggested releases, but in these cases the reason of the deviation (heavy rainfall upstream, forecast of snowmelt, rainfall on the downstream irrigated districts, etc.) is carefully registered. This method of operating will certainly enable the manager to evaluate the real impact of the proposed operating rule and to find systematic ways of improving it.

6. EFFECT OF THE REDUCTION OF THE ACTIVE STORAGE

Besides improving the operating rule, one of the proposals raised by the municipality of Como to alleviate its flood problems was the reduction of the active storage or, more precisely, the reduction of the upper limit $\bar{x}$ of the control range defined in the license act. This proposal is particularly attractive because it can be simply realized by a formal revision of that document.

The effect of reducing the active storage may be quite different depending upon the manager's behavior after the revision has been made. Two possibilities are examined:

(a) The manager, considering that the reduction of $\bar{x}$ has been imposed for flood alleviation, operates in favor of agriculture;

(b) The manager still operates the reservoir by making a tradeoff between the different objectives.

Since hydro-electric power production is relatively insensitive to reservoir operation (see Section 4), the analysis in this section will focus only on the problem of minimizing the annual number of days of flood and the annual deficit of the downstream agricultural users. In particular, only the results relative to an average yearly hydro-electric power deficit of 200 GWh will be shown.

In case (a), the following single objective stochastic problem must be solved:

$$\min_{\{a,b\}} \quad [A]$$

subject to the continuity equation (2) and the set of mass-balance equations describing the downstream distribution network (see Figure 2). In this mathematical program, the value

$\bar{x}$ of the upper limit of the control range appears as a parameter. Since we have only one objective, the solution is unique for each value of $\bar{x}$, and is represented by a single point in the plane (A, F). Again, the solution of this mathematical programming problem has been obtained by simulating the daily behavior of the reservoir in the period from 1965-1979 for different pairs (a, b), thus selecting the optimal values (a^o, b^o). The set of solutions (one for each $\bar{x}$) in the plane (A, F) is represented by curve (a) in Figure 8, (in particular for $\bar{x}$ = 0.80, 0.90,..., 1.30 m).

In case (b), the two objective problem

$$\min_{\{a,b\}} \quad [A \quad F]$$

must be solved for each value of $\bar{x}$. Thus, a set of efficient solutions is generated for each value of $\bar{x}$. In Figure 8, the curves $b_{1.30}$, $b_{1.10}$, and $b_{0.90}$ represent such efficient solutions for $\bar{x}$ = 1.30, 1.10, and 0.90, respectively (obviously, the curve $b_{1.30}$ coincides with the contour line E = 200 GWh of Figure 5). These curves almost intersect each other at point Q, showing that the sensitivity of F and A to $\bar{x}$ is relatively limited, at least within the range of interest. Curve (a), on the other hand, shows that there is a definite interest in reducing $\bar{x}$, at least of 20 cm, because this would reduce the floods in Como even if the manager were biased in favor of agriculture. Furthermore, the reduction of the active storage is very effective at high values of $\bar{x}$, (decreasing $\bar{x}$ from 1.30 to 1.20 m implies a reduction of F from 173 to about 11 days of flood per year with a negligible increase in agricultural deficit (3 million cubic meters)), while it is much less powerful at lower levels (a reduction of $\bar{x}$ from 0.90 to 0.80 m, reduces F by only 0.6 days with a 10% increase in agricultural deficit). From this analysis, it appears that a moderate reduction of the active storage is a convenient decision which, besides being costless, does guarantee under all circumstances, a certain flood reduction, without remarkably increasing agricultural water deficit. Obviously, in terms of floods, better results can be achieved (see point Q in Figure 8) if the manager is not biased.

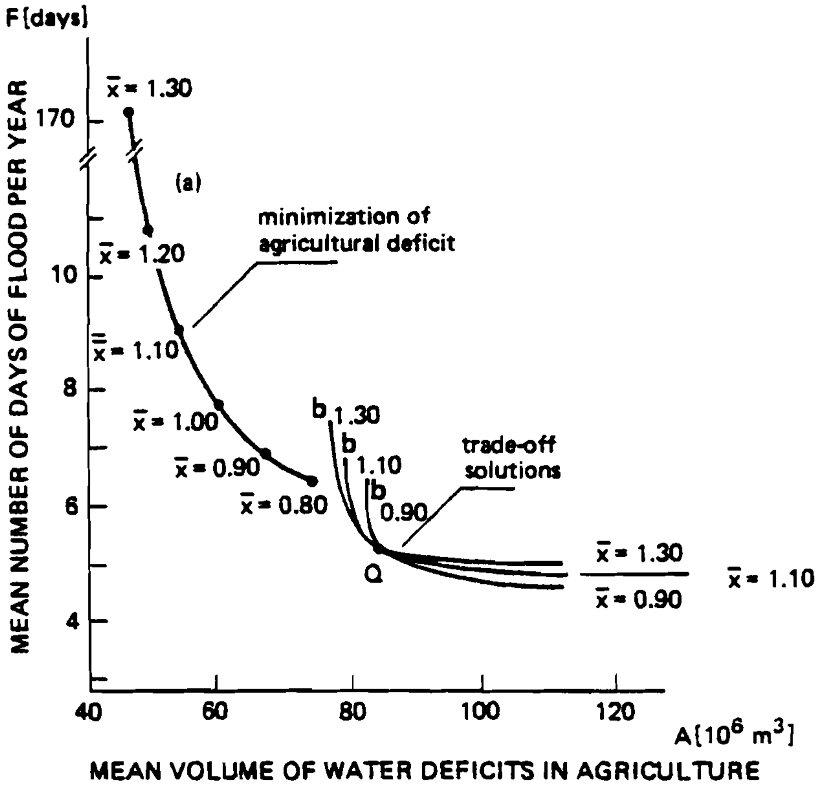


Figure 8. Effects of a variation of the active storage.

From a conceptual point of view, the constant (all over the year) reduction of $\bar{x}$ which has been analyzed here is certainly not the best solution. A more rational proposal would be to impose a seasonally varying upper limit of the control range: the determination of such a periodic variation could easily be done by carefully inspecting the results of the optimization carried out in Sections 4 and 5, since the efficient operating rule proposed in Section 5 is indeed equivalent to a reduction of $\bar{x}$ during the seasons of high inflows. Moreover, one would do even better if the upper limit $\bar{x}$ could be adapted to the current availability of resource, measured for example, in terms of snow cover on the Alps, or depth of the underground aquifer in the lake catchment. Nevertheless, it must be recognized that it would have been relatively difficult to state all these rules in the new license act. Indeed, although we suggested in November 1981 (see Rinaldi (editor), 1981) to lower the upper limit $\bar{x}$ of the control range of 30 cm only during the periods of high inflows (April 15 - May 30 and July 15 - November 10), the Ministry of Public Works finally imposed (June 1982) a 30 cm reduction of $\bar{x}$ during the whole year (at the same time, the lower limit $\underline{x}$ of the control range was also reduced in order to partially compensate the downstream users).

7. PROTECTING COMO SHORES

One of the possibilities of alleviating flood damages in Como is obviously to partially or totally restore 1946 conditions, when the border of the square was at 1.86 m instead of the present 1.24 m. This is, however, a rather costly enterprise, so that a careful analysis is required to optimally choose the degree of protection required.

To examine this problem it is helpful to solve again the multiobjective programming problem presented in Section 4 by parameterizing the value x_c of the lake level at which Como square is flooded. This means that a set of efficient operating rules and the corresponding values of the objectives are computed for each value of x_c.

Figure 9 shows some of these sets (the lowest one corresponds to the situation in 1946 when x_c was equal to 1.86 m, while the third one (x_c = 1.24 m) is again the curve E = 200 GWh of Figure 5). The lowest curve of Figure 9 shows that, if the conditions of 1946 were re-established, the mean number of days of flood per year would be smaller than 1 for a very wide range of agricultural deficits. But even an increase of only 20 cm of the square (from 1.24 to 1.44 m) would entail consistent benefits, reducing to less than half the number of days of flood for all agricultural deficits higher than 80 million cubic meters per year. On the other hand, if the square should continue to sink, the number of days of flood may increase dramatically: for example, 20 days of flood per year would be unavoidable at x_c = 1.04 m, while a sinking of 40 centimeters would imply floods on the square for about 50 days per year on the average.

Protecting the square is thus almost mandatory if sinking should go on, but is definitely appealing even under the present conditions. Indeed, after presentation of these results to the municipality of Como, the repaving and elevation of the road along the lake and of part of the square was immediately considered and should be completed very soon.

8. CONCLUDING REMARKS

This paper has been devoted to the analysis of three different and independent proposals for alleviating flood problems in Como: the modification of the operating rule used up to now by the manager (Sections 3-5), the reduction of the active storage (Section 6), and the protection of the Como square (Section 7). All three proposals have proved to be rather effective. The new operating rule has been programmed on a microcomputer, which is now used every day by the manager as an essential support for the final decision; the upper limit of the control range has been lowered in June 1982 by the Ministry of Public Works, and the sunken part of the town will soon be repaved and elevated.

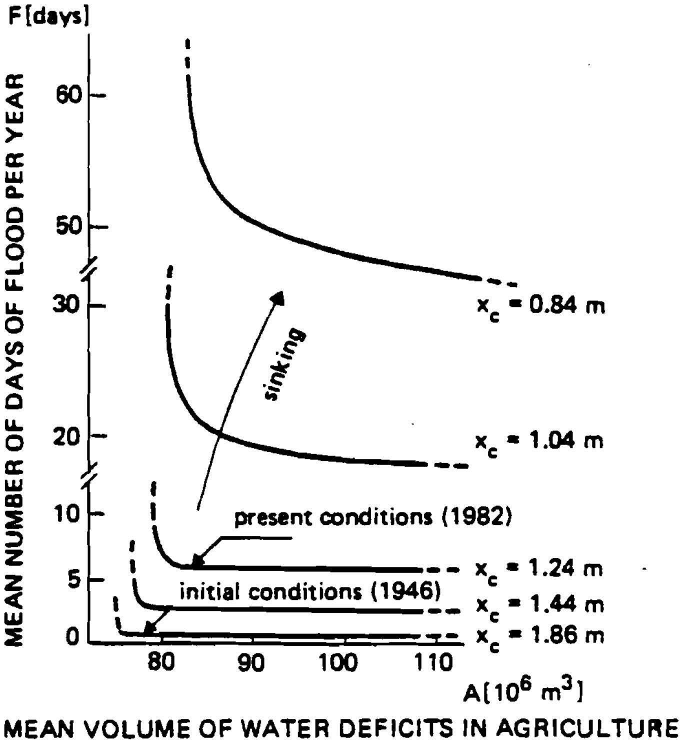


Figure 9. Effects of a variation of the level of Como square (x_c).

The results of the optimization of the operating rule are particularly attractive because they show that the improvements are not at all negligible as one could perhaps imagine. Figure 10 shows four important points in the space (A, F) of the objectives: point N represents the performances of the system in natural conditions (before building the dam); point H shows the historical values of the objectives; point P corresponds to the proposed operating rule; and point U is the "utopia". At this stage, it seems that most of the way leading to the utopia point, (corresponding to the absolute independent minima of the two objectives), has been completed. However, at least in principle, further improvements should be possible, provided that the daily decision is based on a more complete knowledge of the state of the whole system. In this respect, information on the current values of snow cover, amount of precipitation in the last days, depth of the water table in the lake catchment, and so on, may certainly be of help. Indeed, all this information already contributes to the actual decisions of the manager, in particular during floods and droughts. A more systematic use of these data may no doubt contribute to the definition of a more complete and powerful management policy for Lake Como.

The approach followed in this paper is completely empirical and in contrast to other traditional techniques such as linear programming, dynamic programming, and maximum principle. First of all, the identification of the operating rule implicitly used in the past has given the analyst the chance to learn from the experience of the manager. The result of this preliminary analysis is then largely taken into account in the optimization phase. The operating rules from which the efficient ones are selected have indeed the same structure as the identified operating rule, so that the proposed modifications are immediately understood by the manager and easily accepted. This feature is very important in practice and distinguishes the present method from others, which have often failed to be implemented just because their solution was too different from the one currently being used.

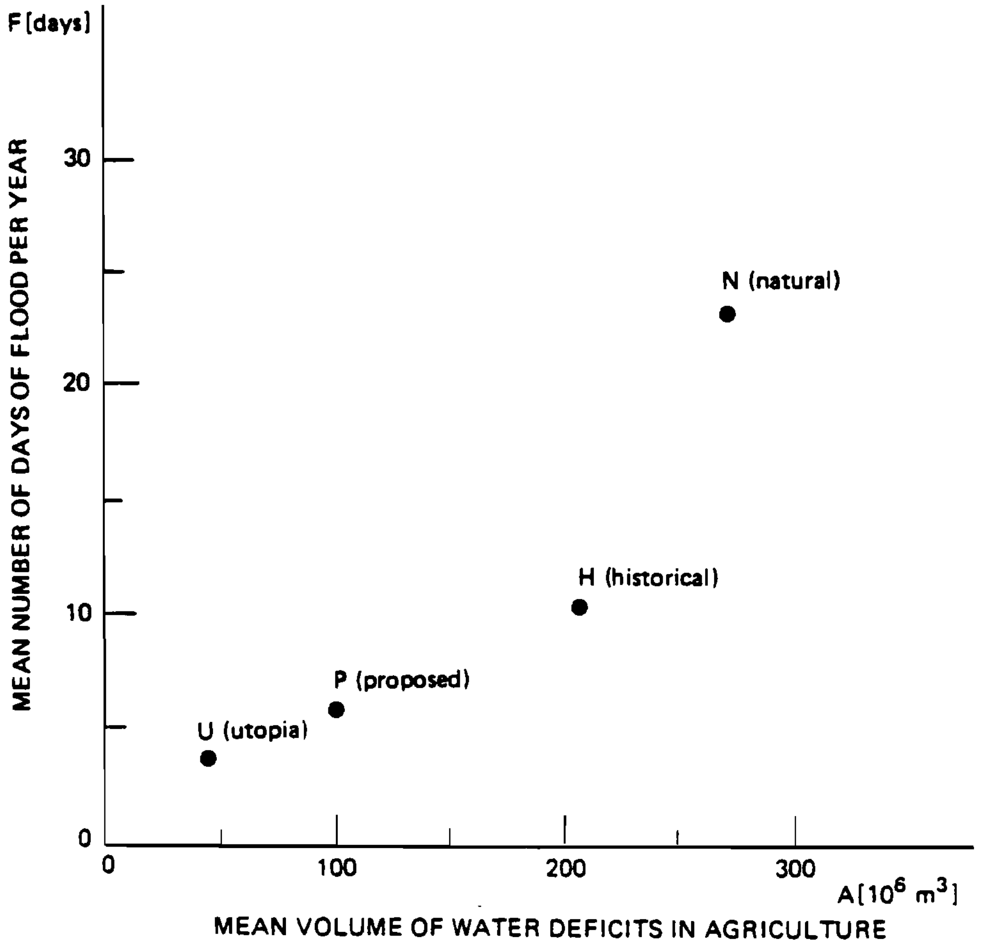


Figure 10. The value of the objectives in different conditions (N = natural conditions; H = historical operating rule; P = proposed operating rule; U = utopia point).

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