Performance evaluation of an irrigation system under some optimal operating policies

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Abstract Three indicators are used to study the performance of a single purpose irrigation reservoir in Karnataka, India. The three indicators are reliability, resiliency and a productivity index. The performance of the reservoir is evaluated when it is operated with optimal operating policies over a sufficiently long period of time. Three different optimal operating policies are derived, having increasing mathematical complexity, using stochastic dynamic programming (SDP). Two of the three policies, Policy II and Policy III, incorporate a detailed soil moisture dynamics model as an integral part of the SDP. Policy III considers, in addition, an optimal allocation of water among the irrigated crops when there is competition for water. The reservoir releases are simulated under each optimal operating policy using synthetically generated inflows, and a comparison of the system performances is made.

L'evaluation des performances d'un système d'irrigation sous quelques regles d'exploitation optimale

Résumé On utilise trois indicateurs pour étudier les performances d'un réservoir à un seul but au Karnataka en Inde. On évalue les performances du réservoir quand il est exploité avec des règles de gestion optimale pendant un durée suffisante. Il y a trois règles differentes d'exploitation optimale, avec une complexité mathematique croissante, en utilisant le programme stochastique dynamique (SDP). Des trois règles, la règle II et la règle III comportent un modèle dynamique détaillé de l'humidité du sol comme partie intégrante du SDP. La règle III considère, en plus une allocation optimale de l'eau parmi les cultures irriguées quand il y a conflit pour l'utilisation de l'eau. Les lâchures du réservoir sont simulées par chaque règle d'exploitation optimale, en utilisant des entrées obtenus par géneration synthetique, et on procède à une comparaison des performances du système.

INTRODUCTION

Applications of systems techniques to water management problems have gained momentum over the years. With the demand for water growing continuously, efforts are being made to manage this important resource

efficiently. The need for a scientific approach is felt especially in the management of reservoirs where large volumes of water are stored for use when needed. The use of mathematical models has greatly aided in providing a good insight into the intricacies of various aspects of problems of water management. In the Indian context, where irrigated agriculture is the most important purpose for which most reservoirs are operated, the development of mathematical models for optimal operation of irrigation reservoirs should receive the greatest attention.

When an optimal reservoir operating policy is derived, based on an objective function, the policy itself does not, in general, indicate how the system would actually perform unless a criterion to this effect is embedded in the objective function. While a systems analyst is interested in arriving at the policy through the use of an objective function, the irrigation manager in charge of operations would look for the implications of using the policy through answers to questions such as how often will the system fail and how quickly will it recover from a failure. It is therefore important that the implications of reservoir operation with a given policy be studied keeping in view the interests of the irrigation manager. In this paper, three performance indicators are discussed to study the implications of the optimal operating policies developed for an irrigation reservoir. The performance indicators are determined for an existing reservoir through a simulation model. The indicators are: reliability, resiliency with respect to water supply, and a productivity index with respect to the crop yield.

A detailed review of reservoir operation models is given by Yeh (1985). Use of stochastic dynamic programming (SDP) for deriving optimal operating policies has become popular in recent years (e.g., Stedinger *et al.*, 1984; Esmaeil-Beik & Yu, 1984; Goulter & Tai, 1985; and Karamouz & Houck, 1987). In the context of reservoir operating policies for irrigation alone, Dudley and his associates (Dudley & Burt, 1973; Dudley *et al.*, 1971a, 1971b, 1972; Dudley, 1988) have contributed a very useful sequence of models, aimed at developing optimal short-, intermediate- and long-run irrigation policies. Rao *et al.* (1990) have dealt with the problem of allocation of a limited water supply for irrigation of several crops grown in the same season. The allocation problem is solved in a dynamic framework by decomposition into two levels, seasonal and intra-seasonal competition for water. They have provided an implementable set of weekly irrigation programmes for individual crops.

In this study, three different optimal operating policies are considered for studying the performance of an irrigation system in India. Stochastic dynamic programming (SDP) is used to derive steady-state operating policies. The system operation is simulated under each of the policies to determine the performance indicators for the case study of Malaprabha Reservoir in Karnataka, India.

OPTIMAL RESERVOIR OPERATION MODELS

Three steady-state operating policies are derived, corresponding to three different objective functions. A major purpose in choosing those policies was to examine the effect on the system performance of increasing detail in the model which determines the operating policy. Accordingly the three objective functions of the policies reflect different degrees of detail. The first policy, Policy I, is derived based on a minimization of the expected value of the squared (overall) deficit. This is a very common objective function for the long term operation of a reservoir (e.g. Loucks *et al.*, 1981). However, in the context of reservoir operation for irrigation, such an objective function will not adequately represent the response of the system. Also, as the demands are all lumped together in the model, allocation of water to individual crops cannot form a part of the model. Policy I is considered in this study mainly as a bench-mark to measure the performance of the other two policies. Policy II and Policy III are improvements over Policy I in that: (a) the soil moisture contribution to meeting the irrigation requirements is taken into account in these policies; (b) allocation among crops of a given amount of water forms the basis for choosing the optimal release policy; and (c) the soil moisture dynamics and the crop response (through evapotranspiration) to water application are explicitly included in the models that determine these policies.

When the water reaching the field is not adequate to meet the total irrigation requirement of the crops, the allocation to individual crops is decided by two different criteria in the two policies. In Policy II, the allocation to a crop is in proportion to its irrigation requirement, a procedure commonly used by irrigation managers at the field level when there is competition for water among the crops. In Policy III, on the other hand, the water available at the field level is optimally allocated among the crops whenever there is competition. The optimal allocation at the field level is based on a detailed accounting of the soil moisture. The reservoir operation model and the field level optimization have thus been integrated in deriving Policy III.

All three policies have been derived for an existing irrigation reservoir system where the cropping pattern is already well defined. In deriving the steady-state policies, therefore, the cropping pattern was assumed to remain the same (as the existing one) from year to year. The policies are derived using SDP. The inflow to the reservoir is treated as a stochastic state variable in the SDP for all three models. The formulation of the recursive equations of the SDP is done following Loucks *et al.* (1981) and the equations solved over a long enough number of periods to obtain a steady-state operating policy. All state variables are discretized into a convenient number of class intervals and any value of a state variable within a class interval is represented by the midpoint of the class. The main features of the mathematical formulations used to derive the policies are discussed below.

POLICY I

This is, mathematically, the simplest policy. The objective function for this policy is:

$$\text{Min } E(R_{kilt} - D_t)^2 \qquad \forall\ k,\ i;\ l \text{ feasible}$$

where: E is the expectation operator; R_{kilt} is the release when the reservoir storage at the beginning of the period t belongs to the storage class k of period t; that at the end of the period t (or beginning of the period $t + 1$) belongs to the storage class l of period $t + 1$; the inflow during the period t belongs to the inflow class i of period t; and D_t is the irrigation demand from the reservoir during period t.

In the above formulation, only two state variables are considered, viz., the reservoir storage and the inflow to the reservoir. The total irrigation demand D_t from the reservoir during period t is computed based on the potential evapotranspiration ($ET_{\max}$) of a crop and the rainfall contribution. The total demand in period t, which in this case is independent of the state variables, is given by:

$$D_t = \sum_{c=1}^{N} (ET^c_{\max,t} - RAIN_t) A_c \qquad (1)$$

where: $ET^c_{\max,t}$ is the potential evapotranspiration of the crop c in period t; $RAIN_t$ is the rainfall contribution in period t; A_c is the area over which crop c is grown; and N is the number of crops present in period t. This way of computing the demand implies that the evaporative demand of a crop is met either by rainfall alone or by rainfall and irrigation. The soil moisture contribution to meeting crop water demand is neglected. The release policy is then derived based on this total demand. The policy itself thus does not say anything about how the released water must be allocated to individual crops. That problem is left to the discretion of the decision maker. When the released water is not adequate to meet the total demand in the field, it may be allocated equally among all the crops or in proportion to the requirements of individual crops. Because the water that is released from the reservoir is finally used by the crops in the form of evapotranspiration, it is imperative that, when deriving the release policy for the reservoir, the strategy adopted to distribute the released water among the crops also forms a basis for the particular release to be chosen as optimal. That is, the criterion by which the water released from the reservoir is allocated among the crops must be embedded in the model that determines the release policy. The other two policies, Policy II and Policy III, have this important feature. They differ, however, in the criterion by which the water is allocated among the crops; while in Policy II it is allocated by simple proportioning, Policy III uses an optimization process to allocate the water among different crops.

POLICY II

When the water released from the reservoir is not adequate to meet the total irrigation demand in a period, a competition for water exists among the crops in that period. It is important that in such a case the allocation of the available water to individual crops be done such that the adverse effect of the water deficit is minimized. Also, the criteria used for the allocation of water among crops in the face of competition must be included in the optimization model that derives the steady-state operating policy.

Policy II is similar to Policy I in that the objective function considers the overall demand during a period. However, in deriving Policy II, the variability in the demands of individual crops due to the contribution of soil moisture is taken into account by introducing a third state variable in addition to the reservoir storage and inflow. The average soil moisture in the irrigated area at the beginning of a period is treated as the third state variable. Although for an accurate representation of reality the soil moisture dynamics of individual crops must be considered, this would mean inclusion of one soil moisture state variable for each of the crops, and hence would be computationally very expensive.

The irrigation strategy used in this study is to apply irrigation to a crop c in period t only when the available soil moisture in the root zone is below a critical level. The critical level of available soil moisture is chosen corresponding to the soil moisture level below which the actual evapotranspiration becomes less than the potential evapotranspiration. The amount of irrigation is such that it raises the soil moisture in the root zone to field capacity, if possible. Thus, the irrigation requirement of a crop c during a period t is given by:

$$\begin{aligned} IRR^t_{c,m} &= 0 \qquad \text{if } (\theta^t_m - Z_w)D^t_c + RAIN_t \geq (1-d)(Z_f - Z_w)D^t_c \\ &= \left[Z_f\, D^t_c - (\theta^t_m D^t_c + RAIN_t)\right]A_c \qquad \text{otherwise} \end{aligned} \tag{2}$$

where: $IRR^t_{c,m}$ is the irrigation requirement of the crop c in period t (in volume units) when the soil moisture state at the beginning of the period is m; θ^t_m is the representative value of the soil moisture class m in period t; D^t_c is the root depth of crop c in period t; d is the soil moisture depletion factor; A_c is the area over which the crop c is grown; and Z_f and Z_w are the soil moistures corresponding to field capacity and wilting point, respectively. The soil moistures Z_f, Z_w and θ^t_m are in depth per unit depth (of root zone) units.

The objective function for Policy II is written as:

$$\text{Min } E(X_{kilt} - D^m_t)^2 \qquad \forall\ k, i, m; \ l \text{ feasible}$$

where X_{kilt} is the water reaching the field after losses when a release R_{kilt} is

made at the reservoir and D^m_t is the total irrigation demand of the crops when the soil moisture state at the beginning of the period is m and is given by:

$$D^m_t = \Sigma_c IRR^t_{c,m} \tag{3}$$

For determining the soil moisture at the beginning of the next period, $t + 1$, the irrigation application to individual crops needs to be considered. If the water available for irrigation (X_{kilt}) is adequate to meet the total demand D^m_t, then each crop is allocated its full requirement. If, on the other hand, X_{kilt} is less than the total requirement then the available water is allocated in proportion to the requirement of the individual crops.

Thus:

$$\begin{aligned} IRA^t_{c,m} &= IRR^t_{c,m} && \text{if } X_{kilt} \geq D^m_t \\ &= IRR^t_{c,m} X_{kilt}/D^m_t && \text{otherwise} \end{aligned} \tag{4}$$

where $IRA^t_{c,m}$ is the irrigation allocation to crop c in period t when the soil moisture state is m. With this allocation, the soil moisture at the end of the current period is determined, and is corrected for the root growth from period t to period $t + 1$ to obtain the soil moisture state at the beginning of the period $t + 1$. The details of the soil moisture balance used are given elsewhere (Mujumdar, 1988).

Thus, in obtaining the release policy, the objective function also considers the allocation among the crops. That allocation, however, is not necessarily optimal from a crop yield point of view, i.e. the allocation process itself is a simple proportioning and is not based on how a crop responds to a deficit in water supply. Also, by allocating the available water in proportion to the water requirement in the presence of competition, all crops and all periods are treated alike.

POLICY III

Conceptually, Policy III is an improvement over Policy II. While retaining all the features of Policy II, it includes an optimal allocation process in the model that determines the optimal release policy. When competition for water exists among the crops, instead of allocating the water in proportion to the irrigation requirements of the individual crops, the allocation is done through an optimization model which then forms a part of the SDP model that determines the optimal release policy.

The objective function for this policy is written as:

$$\text{Min } E[\text{Min } \Sigma_c (IRR^t_{c,m} - IRA^t_{c,m})^2_{kilt}] \qquad \forall\, k, i, m; \; l \text{ feasible}$$

The term within the brackets represents the objective function for the sub-optimization when there is competition for water. When there is no competition, the allocation is made equal to their respective requirements, and the soil moisture balance is carried out. The sub-optimization is modelled using deterministic dynamic programming in which individual crops form the stages and the water remaining to be allocated over the remaining stages forms the state variable. The objective function values of the sub-optimization enter the main optimization (SDP) as inputs. The recursive equations of the two dynamic programs, one deterministic and the other stochastic, are quite straightforward and hence are not included here.

Between Policy II and Policy III, both of which consider allocation among crops of a known quantity of available water when competition for water exists among them, it would be interesting to analyse the allocation procedures used. A deficit of water is proportionally shared by all the crops in the case of Policy II. That is, when a deficit occurs, all the crops suffer for lack of water in the same proportion as their individual requirements. That allocation is reflected in determining the soil moisture at the end of a period. In Policy III on the other hand, the allocation process is itself an optimization process and directly feeds into the main optimization procedure that determines the optimal release from the reservoir. The objective function of the sub-optimization however does not take into account how an individual crop may suffer in the event of a deficit in water supply in terms of its yield. It only minimizes the overall squared deficit during a period. Thus it is possible that a crop gets its full requirement in a period and does not get any water in the next, when competition exists in both periods. This may affect the crop yield adversely.

PERFORMANCE OF THE SYSTEM UNDER THE OPTIMAL POLICIES

All three policies discussed above take into account the stochastic nature of the inflows through their transition probabilities. Since the policies are determined on a long term basis, they imply an optimal operation only when implemented over a long enough period of time. Also, the objective functions on which the policies are based are quantitative with respect to the amount of deficit that occurs and not with respect to the number of times a deficit occurs. In view of this it would be interesting to study the operation of a reservoir under such optimal policies and measure the performance of the system through some indicators which address somewhat different questions than those considered in the objective functions of the policies, but which may be of practical interest to a project manager in analysing the implications of the policies when adopted in practice to a real situation.

Performance indicators

Three performance indicators were chosen to study the performance of a system under a given operating policy. They are: (a) reliability; (b) resiliency (with reference to the adequacy of water supply to meet the irrigation requirement); and (c) a productivity index (with reference to crop yield).

The reliability of a system under a given operating policy is defined as the probability that the system output is satisfactory (Hashimoto *et al.*, 1982). The system output in this study is defined to be satisfactory in a given period t if the water available for irrigation, $X_t = \beta R_t$ (where R_t is the release from the reservoir in period t and β is the field irrigation efficiency), is at least equal to the total irrigation requirement of all the crops in that period.

This definition of reliability simply reflects the likelihood of a non-failure without specifying the extent of a failure when one occurs. It still provides a good measure of the ability of the system in providing the required irrigation.

While the system reliability gives the likelihood of a satisfactory performance, resiliency gives the likelihood of the system recovery from a failure once a failure occurs. If the recovery from failure is slow it may have serious economic implications. A higher resiliency would mean a quicker recovery from failure and hence one would prefer policies having high resiliency as well as high reliability.

The definition of resiliency is adopted from Hashimoto *et al.* (1982) for the present study. Mathematically, the resiliency γ of a system is defined as the inverse of the expected value of T_U, the length of time (number of periods subsequent to a failure period) that the system output remains unsatisfactory after a failure, i.e.:

$$\gamma = 1/E(T_U) \tag{5}$$

This definition, after some mathematical treatment (Hashimoto *et al.*, 1982) reduces to:

$$\gamma = P(X_{t+1} \in V_{t+1} / X_t \in U_t) \tag{6}$$

where V_t is the set of all satisfactory outputs in period t and U_t is the set of all unsatisfactory outputs in period t. Expressed in words, resiliency is given by the probability that the system output in period $t + 1$ is satisfactory, given that it is unsatisfactory in period t.

The two performance indicators, reliability and resiliency, do not reflect the effect of a failure. For example, they do not indicate by how much crop yields will suffer. Even with a high reliability, crop yields may still be low if the failures occur in critical periods of the growing season of a crop, or if the failures occur successively or if the deficits in a period are so large as to cause permanent damage to the crop. It is therefore of interest to study the system performance with reference to the crop yields resulting from an operating policy.

An index, called here the productivity index, is defined as a measure of the relative yields of the crops. It is defined as the probability that the average of the relative yields among all the crops in a year is greater than a specified value λ. That is:

$$\eta = P\left[(y/y_m)_{av} \geq \lambda\right] \tag{7}$$

where $(y/y_m)_{av}$ is the average relative yield (ratio of the actual yield y to the maximum yield y_m) of the crops in a year.

The determination of the productivity index requires the estimation of the relative yields of each of the crops in each year of simulation by an appropriate production function. In this study, the multiplicative production function (Rao *et al.*, 1990) is used and is of the form:

$$(y/y_m)_c = \Pi_{s=1}^{NS}\left[1 - ky_s^c(1 - ET_a^c/ET_{\max}^c)s\right] \tag{8}$$

where: $ky^c{}_s$ is the yield factor of crop c in growth stage s; $(y/y_m)_c$ is the relative yield of the crop c; s is the index for a growth stage; and NS is the number of growth stages of the crop c.

The actual evapotranspiration $ET^c{}_a$ is a function of the irrigation allocation, rainfall, initial soil moisture, depth of the root zone and potential evapotranspiration.

Different values of λ define different productivity indices for the same policy. A higher λ would, in general, result in a lower productivity index. For this reason it would be interesting to study the tradeoff between the productivity index and λ.

The index η, like reliability, gives a measure of the overall performance of the system, but in terms of the relative yields of the crops instead of adequacy of water supply. However, it does not serve as an explicit measure of the individual crop yield in a multiple crop environment.

In order to determine a specific performance indicator for a given policy, the system is simulated over several years using synthetically generated streamflows. A Thomas-Fiering model (Fiering & Jackson, 1971) is used for streamflow generation. The optimal release to be made from the reservoir during a period is obtained from the optimal policy for the known conditions of initial reservoir storage, inflow during the period (generated value) and the average soil moisture in the irrigated area at the beginning of the period. That release is made from the reservoir when possible and the reservoir storage is updated. Out of the release made from the reservoir, water is allocated after accounting for the losses to individual crops according to the criterion used for allocation in deriving the particular optimal policy (proportioning in the case of Policy II and optimal allocation using dynamic programming in the case of Policy III). Policy I does not consider the soil moisture variation and allocation among crops. The productivity index is therefore not determined for Policy I.

In the case of the two policies which consider soil moisture as a state variable, the soil moisture at the beginning of the next period in simulation is obtained through a soil moisture balance for the individual crops. Thus, while the average soil moisture is used for making the release decision at the reservoir, the soil moisture variation of individual crops is considered for the purpose of computing irrigation requirements and actual evapotranspirations. A linear root growth model is used for all crops. In determining the soil moisture for a crop at the beginning of the next period, the moisture θ_0 initially present in the layer of soil added to the root zone in that period is taken into account.

APPLICATION TO A CASE STUDY

The optimal policies and the performance indicators discussed in the previous sections were determined for the case study of the Malaprabha reservoir project in the Krishna Basin of Karnataka state, India. It is a single purpose irrigation reservoir which has been in operation since 1973. Located in the northern region of Karnataka state, the reservoir has a major portion of the irrigated area in black cotton soil. The major crops grown in the command area are cotton, wheat, sorghum, maize, safflower, groundnut and pulses. The reservoir has a gross storage capacity of 1070 M m^3 and a live storage capacity of 870 M m^3. Figure 1 shows the location map of the Malaprabha reservoir.

As the moisture holding properties of the soils in the left bank and right

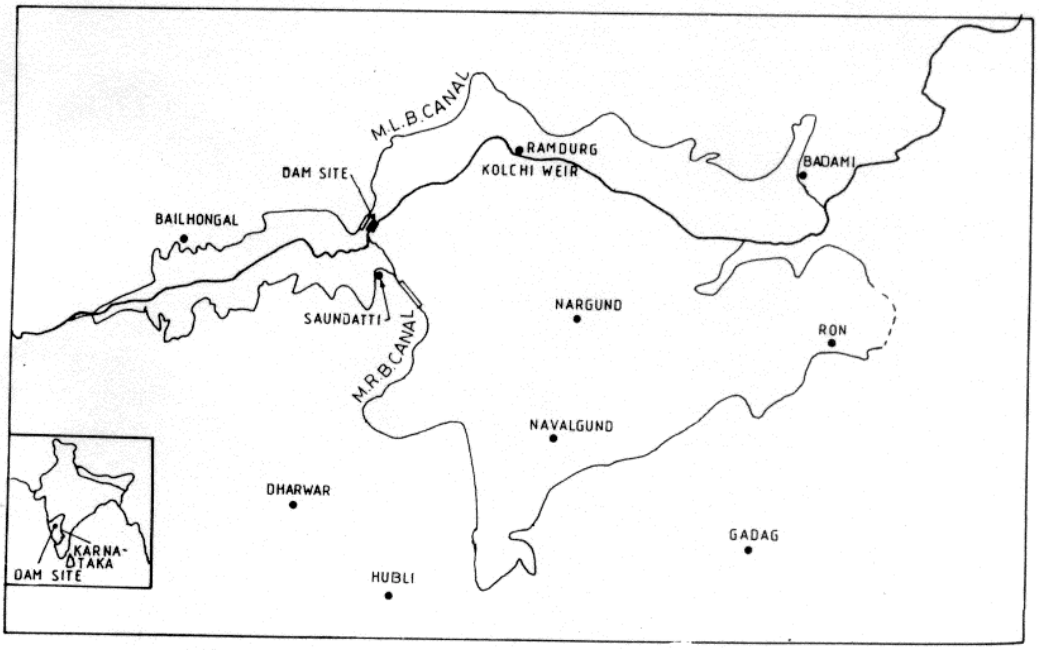

Fig. 1 Location map of Malaprabha Reservoir.

bank area are different, the model is applied only to the right bank area with the assumption (supported by studies on areas irrigated and the total water requirements of the two areas) that, out of the release from the reservoir, one third is diverted to the left bank canal and the remaining two thirds are available for irrigating the crops in the right bank area consisting of black soil. The optimal policy for the reservoir operation was derived based on allocation of the available water among the crops grown in the black soil. A water year (1 June to 31 May) was divided into 36 10-day periods. The duration of the last few periods was increased by one day each to compensate for the additional number of days over 360 in a given year. Figures 2, 3 and 4 give some details of the case study.

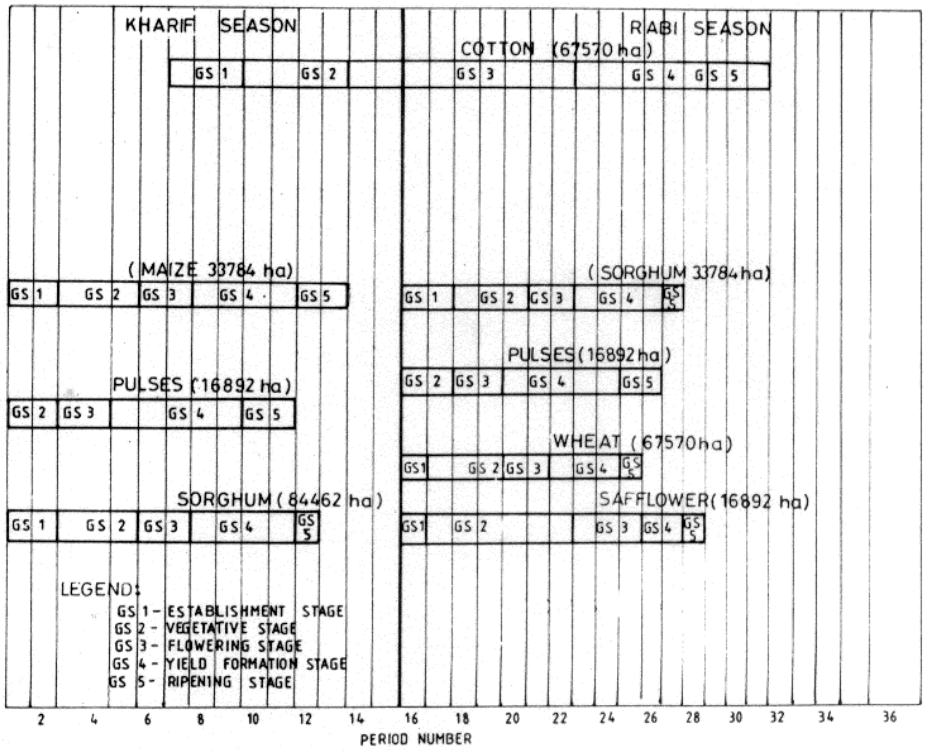

Fig. 2 Crop calendar.

The principal crops and the cropping pattern for the area irrigated by the right bank canal are shown in Fig. 2. For the purpose of deriving the operating policy, that cropping pattern was assumed to remain the same every year. The growth stages were adjusted to be multiples of the decision intervals (of 10 days) making use of the available information from Doorenbos & Kassam (1979).

Table 1 shows the values of the performance indicators obtained for the system under the three optimal policies when the simulation was carried out for 400 years. It is noted that although the general feature of the three objective

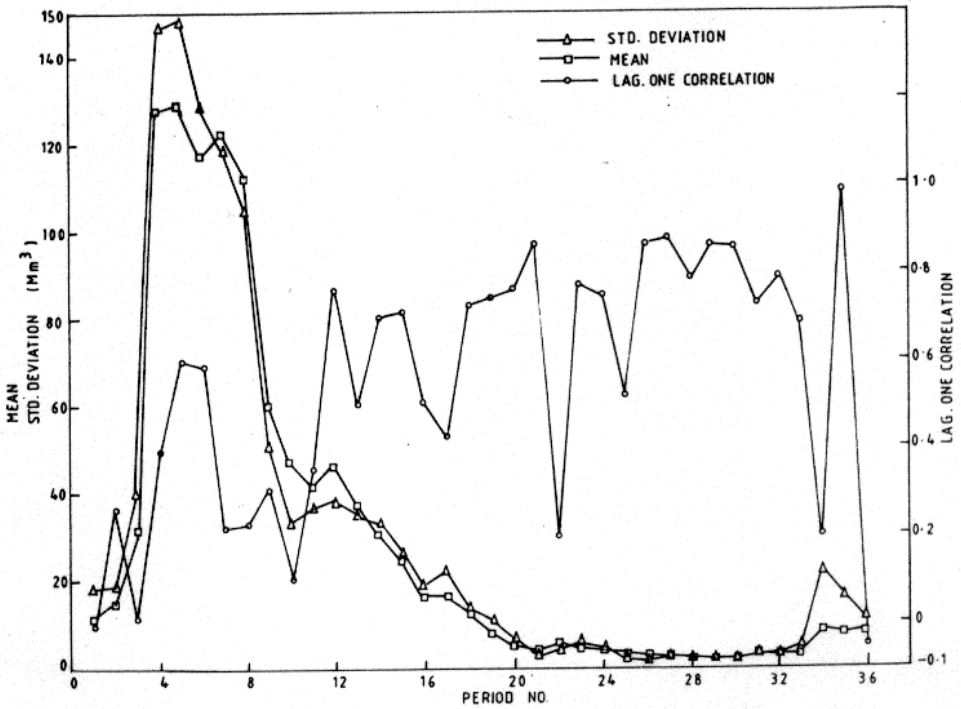

Fig. 3 Statistical properties of inflows.

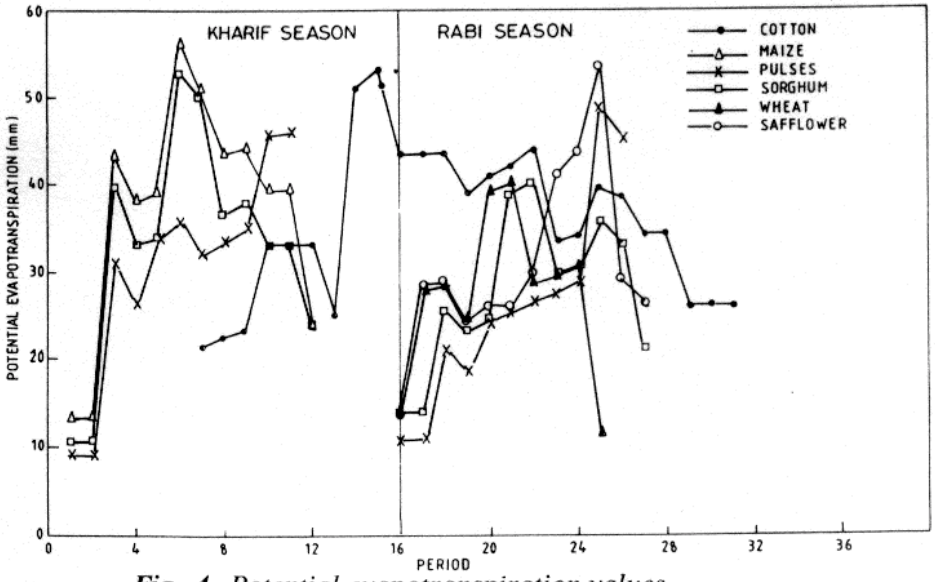

Fig. 4 Potential evapotranspiration values.

functions is the same (namely, minimization of the expected value of deficits), there is a fairly large difference between the reliability resulting from Policy I,

that from Policy II and that from Policy III. This result is not very surprising. The region being modelled is situated in the drought-prone area of North Karnataka in India. The rainfall contribution to the crop growth in that region is either low or moderate, and hence the crops have to be largely sustained by irrigation alone, especially in the non-monsoon Rabi season. In that light, the contribution of the soil moisture storage towards meeting the crop water requirements gains a great importance. Policy I, by neglecting that important aspect, stresses the reservoir with a greater demand for water and thus results in a lower reliability. It may be observed that the performances of the system under Policy II and Policy III, being always better than that under Policy I in terms of both reliability and resiliency, depend rather heavily on θ_0, the initial soil moisture value used for the layer of soil added to the root zone in a period. Because the soil moisture front advances downwards after the moisture level in a layer reaches field capacity, it is possible that the initial soil moisture θ_0 may be anywhere between wilting point and field capacity. The performance of the system is studied for two values of θ_0, one at 3.5 mm cm^{-1} (being the field capacity in the irrigated area) and the other at a lower value of 2.5 mm cm^{-1}. Table 1 indicates that, at the higher value of θ_0, the performance of the system was very good under both policies. At the lower value of θ_0, however, the system performed better under Policy II than under Policy III.

Table 1 *Performance values for the policies*

Policy	Reliability	Resiliency	Productivity index (λ)			
			0.90	0.92	0.94	0.96
Policy I	0.633	0.458				
Policy II$^+$	0.956	0.968	1.0	1.0	0.963	0.0
Policy II*	0.879	0.687	1.0	1.0	0.921	0.0
Policy III$^+$	0.996	0.954	1.0	1.0	0.855	0.0
Policy III*	0.894	0.224	0.663	0.453	0.150	0.0

+ with θ_0 = 3.5 mm cm^{-1} (field capacity); * with θ_0 = 2.5 mm cm^{-1}.

Although both policies resulted in high reliability, Policy III resulted in a very low resiliency (at the lower value of θ_0). When using Policy III, there-fore, if a failure occurs, the likelihood of recovery from failure is very small, and this contributes to the cause of the low productivity index. Also, the sub-optimization used in Policy III (optimization of allocation among different crops) does not aid in improving the productivity. It minimizes the sum of deficits without regard to how a crop would respond to a particular deficit. It is thus likely that a very large deficit occurs in a period when the crop growth is highly sensitive to a water deficit, which would result in a low yield of the crop, even if the crop is allocated with its full requirement in other periods. Policy II, on the other hand, distributes the water available for irrigation in proportion to the individual crop requirements and thus a uniformity is maintained, which resulted in a higher productivity index. It is an important conclusion drawn from the results that the

system reliability by itself is not adequate to measure the performance of an irrigation system, and it is essential to study the crop response to a water deficit to get a better idea of the system performance.

CONCLUSION

Three performance indicators are discussed in this paper to evaluate the performance of a single purpose irrigation reservoir. Those indicators were determined for the case study of Malaprabha Reservoir in Karnataka, India, when three different optimal operating policies were used for its simulated operation. The three indicators are reliability, resiliency and a productivity index. They reflect, respectively, the ability of a system to meet the demand, recover from a failure and produce crop yield. The three optimal operating policies were derived for the system, each with a different objective function, using stochastic dynamic programming, and the simulated performance of the system under these policies was compared. It was observed that including the soil moisture dynamics into the optimization model that derives the operating policy for the reservoir enhances the performance of the system.

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