Xth World Water Congress, Melbourne, Australia, March 12-16, 2000, paper no. 0193

Resiliency Estimates for Irrigation Systems

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ABSTRACT

In this paper, the criteria and methodologies proposed by Hashimoto et al (1982) and Fiering (1982), for estimating resiliency are applied to an irrigation system consisting of a single reservoir serving multiple crops. The resiliency is related to the soil moisture depletion. The failure index is determined based on the irrigation deficit occurring in a period. Partial failures are considered by defining a demand factor. The methodology is demonstrated for a case study in India.

KEYWORDS

Resiliency, Irrigation, Reservoir Operation, Simulation, Crop Response.

INTRODUCTION

The criteria of reliability, resiliency and vulnerability are most commonly used for the performance evaluation of water resources systems. The resiliency of the system denotes the ability of the system to recover from failure, once a failure occurs. In irrigation systems, the resiliency is the most vital performance criterion since a low resiliency would mean poor crop yield even when the reliability of the water supply is high, as the timing of irrigation is as important as the quantity of irrigation itself. In drought prone regions with severe water shortages, it is necessary that the irrigation policies be evaluated for their resiliency before actual implementation.

In this paper, the criteria and methodologies proposed by Hashimoto et al (1982) and Fiering (1982) for estimating resiliency are applied to an irrigation system consisting of a single reservoir serving multiple crops. The measure of resiliency is related to the soil moisture depletion. The failure index is defined based on the evapotranspiration deficit occurring in a period. Partial failures are considered by defining different failure thresholds. The methodology is demonstrated for a case study in India. The resiliency estimates are computed from a simulated operation of the irrigation system, with a long term operating policy derived from a stochastic dynamic programming model. In an earlier study (Mujumdar and Vedula, 1992), different performance criteria have been derived for irrigation systems, with integrated operation of the reservoir and the field-level irrigation scheduling. Effect of resilience on crop yield is also discussed in that study. That study is extended in the present paper to include partial failures of the system related to the evapotranspiration deficits. The methodology of estimating resiliency is demonstrated through a case study.

RESILIENCY OF IRRIGATION SYSTEMS

Resiliency describes how quickly a system is likely to recover or bounce back from failure, once a failure has occurred. Hashimoto et al (1982) have shown that this definition of resiliency results in resiliency being equivalent to the average probability of a recovery from the failure set in a time step. That is,

$$\gamma = \text{Prob}\ \{X_{t+1} \in S \mid X_t \in F\} \qquad (1)$$

where γ is the resiliency, X_t is the system output in period t, S and F are respectively the sets containing acceptable (success) and unacceptable (failure) outputs. Fiering (1982) developed methodologies to include partial failures in the estimates of resiliency. A full failure may be defined, for example, to be a failure to supply 75% of the target in a water supply system, and other partial failures may be similarly defined. Weighatges are thus attached to the extent of failure occurring in a period, while determining system resiliency.

In the context of irrigation systems, failure during a period may be related to the soil moisture level of a crop during the period, by defining the irrigation requirements based on the amount of water required to bring the soil moisture to field capacity, for a given initial soil moisture of the crop. Also, when operation of an irrigation reservoir is integrated with on-field utilization of water, the outputs of the system should be measured not simply in terms of the reservoir release, but in terms of the crop response to a deficit supply. Some significant studies on integrated operation of irrigation systems may be found in Dudley (1988) and Dudley and Scott (1993). A good measure of crop response is the evapotranspiration deficit, $(1\text{-}Et_a/E_{tmax})$, where Et_a is the actual evapotranspiration of the crop, which is a function of the irrigation water applied, the soil moisture, climate and crop and soil parameters, and E_{tmax} is the maximum (potential) evapotranspiration of the crop under ideal conditions. For the purpose of computing the resiliency, the irrigation requirements of a crop c in period t – which determine the target release from the reservoir – are computed based on the available soil moisture in period t at crop c.

Soil moisture balance between period t and period t+1 is written as,

$$\theta_c{}^t{+}1D_c{}^{t+1} = \theta_c{}^t D_c{}^t + RAIN_t + x_c{}^t - ET_{ac}{}^t + \theta_0(D_c{}^{t+1} - D_c{}^t) - Dp_c{}^t \ \forall c,t \qquad (2)$$

where $\theta_c{}^t$ is the soil moisture (mm/cm), $D_c{}^t$ is the root depth, $x_c{}^t$ is the irrigation allocation $ET_{ac}{}^t$ is the actual evapotranspiration, $Dp_c{}^t$ is the deep percolation – all for crop c in period t – , $RAIN_t$ is the rainfall in command area in period t, and θ_0 is the initial soil moisture in the soil added to root zone between period t and period t+1. Details of the soil moisture balance are given in Mujumdar & Vedula (1992). The irrigation allocation to a crop in a period is decided based on the policy used for operation of the system. For computing the resiliency, the irrigation allocations form the supply and the total irrigation requirements of crops, the target. Partial failures are considered through a failure index defined as,

$$F_t = \Delta_t \,/\, (\alpha\ T_t) \qquad (3)$$

where Δ_t is the deficit during period t, T_t is the target during period t and (1-α) is the fraction beyond which a full failure is accounted. α is called here the demand factor. For example, failure to meet 75% of the target may be deemed as full failure in a period, in which case $\alpha = 0.25$. The extent of recovery from failure between period t and period t+1 may be measured by $F_{t+1} - F_t$, when a failure occurs in period t. The target T_t is determined from,

$$T_t = \sum_{c=1}^{n} IRR_c^t \tag{4}$$

where IRR_c^t is the irrigation requirement of crop c in period t and n is the number of crops present in period t. The irrigation requirement, IRR_c^t is determined based on the known soil moisture of the crop. The policy of irrigation used for computing the irrigation requirements is to bring the soil moisture to field capacity whenever the soil moisture in a period is below a critical level. That is,

$$IRR_c^t = 0 \qquad \text{if} \quad \theta_c^t D_c^t + RAIN_t - \theta_w \geq (1-d)(\theta_f - \theta_w)$$

$$= [\theta_f D_c^t - (\theta_c^t D_c^t + RAIN_t)] A_c \quad \text{otherwise} \tag{5}$$

where θ_f is the field capacity, θ_w is the wilting point, d is the soil moisture depletion factor and A_c is the area in which crop c is grown.

For a specified α, the resiliency is estimated as the weighted average of recovery over the periods in which failure occurred.

RESULTS

A case study of the Malaprabha irrigation reservoir in India has been considered. Relevant data pertaining to the case study are given in Mujumdar and Vedula (1992). A year consists of 36 ten-day periods, with Kharif season from period 1-15 and Rabi season from periods 16-31. There are four major crops in Kharif season and five in Rabi season. An optimal operating policy derived for the case study using a stochastic dynamic programming (SDP) model, with three state variables, reservoir storage, inflow and crop soil moisture, is used to simulate the system operation. The inflow uncertainty is considered through a one step Markov chain. Synthetically generated inflows for 200 years are used for simulation. To examine the effect of partial failures on the resiliency, various values of α are used to compute the resiliency. Results of one year simulation are given in Table 1. In the results given in Table 1, the actual water available for irrigation at the field level is less than the release made at the reservoir, since the crops of only the Right Bank command are considered, and conveyance losses are accounted for the release. The allocations to crops are made with a DP water allocation model. Fig. 1 shows the variation of resiliency with demand factor α.

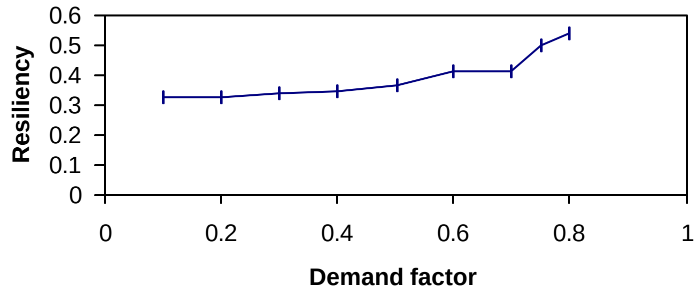

Fig. 1. Variation of resiliency with demand factor

The values of resiliency obtained are relatively low, being in the range of 0.3-0.6. In fact, a realistic value of α may be in the range of 0.2-0.3 (indicating a full failure when the irrigation supply is below 80-70% of the target). In this range, the resiliency is seen to be around 33%. Such low values of resiliency may be explained from the operating policy used for simulation. In the SDP model used for deriving the optimal operating policy, no feature is built in to maximize either the reliability or the resiliency. Also, in the case of competition for water among crops, the SDP model allocates water among crops optimally, by considering the crop response, through the evapotranspiration deficit, only during that period, without considering the interdependency of allocations across periods (Mujumdar and Ramesh, 1997). When the system operation was simulated with the standard operating policy (of simply making supply equal to demand whenever available water is adequate, and meeting demands to the best extent possible with available water when it is not), and without considering the soil moisture variability, the resulting resiliency was obtained as 0.39 for α=0.2, which is only slightly higher than the one obtained with the optimal policy. A more rigorous sensitivity study will be necessary to conclude on the variability of resiliency.

CONCLUSION

Resiliency estimates are obtained for an irrigation reservoir through simulated operation with an optimal operating policy. The failure of the system is defined based on the soil moistures resulting from optimal crop allocations determined by the operating policy. Partial failures are considered by defining a failure index. More rigorous studies are necessary to analyze the sensitivity of resiliency of an irrigation system, when integrated operation is considered.

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Table 1. Results of simulation (one year)
(Demand factor = 0.3)

Period	Storage M.cum	Inflow M.cu.m	Crop Soil Moistures(mm/cm) Crop1	Crop2	Crop3	Crop4	Crop5	Release M.cu.m	Crop Allocations M.cu.m Crop1	Crop2	Crop3	Crop4	Crop5	Failure Index
1	368.81	27.01	1.04	1.04	1.04	1.04	*	45.82	0.00	9.51	0.00	11.89	*	2.62
2	350.00	3.78	1.00	1.00	1.00	1.00	*	3.78	0.00	1.76	0.00	0.00	*	3.28
3	350.00	68.06	1.00	1.00	1.00	1.00	*	45.56	0.00	9.45	7.09	4.73	*	2.66
4	372.50	256.27	1.00	1.00	1.00	1.00	*	203.77	0.00	21.14	10.57	63.43	*	0.36
5	425.00	95.10	1.00	1.41	1.52	1.72	*	0.00	0.00	0.00	0.00	0.00	*	0.00
6	520.10	107.81	1.28	1.30	1.46	1.61	*	0.00	0.00	0.00	0.00	0.00	*	0.00
7	627.90	134.43	1.56	1.02	1.39	1.33	*	52.33	0.00	13.58	0.00	10.86	*	0.32
8	710.00	184.26	1.00	1.24	1.00	1.00	*	214.26	33.35	11.12	11.12	44.46	*	0.86
9	680.00	47.27	1.22	1.00	1.51	1.10	*	40.27	14.62	4.18	0.00	0.00	*	0.89
10	687.00	52.22	1.00	1.00	1.00	1.00	*	52.22	0.00	10.84	0.00	13.54	*	2.81
11	687.00	57.32	1.00	1.00	1.00	1.00	*	0.00	0.00	0.00	0.00	0.00	*	0.00
12	744.32	84.23	1.12	1.05	1.00	1.05	*	0.00	0.00	0.00	0.00	0.00	*	0.00
13	828.55	45.01	1.36	1.39	1.57	1.38	*	3.56	1.67	0.00	0.00	0.00	*	0.00
14	870.00	96.24	1.69	1.91	2.10	1.90	*	96.24	45.14	0.00	0.00	0.00	*	0.00
15	870.00	46.53	3.20	2.29	2.47	2.28	*	46.53	4.28	8.56	0.43	8.56	*	0.00
16	870.00	0.00	3.11	3.20	2.82	2.87	1.16	23.41	0.00	0.00	0.00	0.00	10.93	0.32
17	846.59	37.15	1.89	2.15	2.20	2.18	3.50	13.74	1.79	1.43	1.43	0.72	1.07	0.00
18	870.00	24.66	1.62	2.17	2.37	2.02	3.47	24.66	3.21	2.57	2.57	1.29	1.93	0.00
19	870.00	11.03	1.36	2.11	2.59	1.84	3.50	11.03	1.18	0.94	0.82	1.53	0.71	0.00
20	870.00	7.81	1.05	1.96	2.56	1.69	3.39	42.81	15.55	0.00	0.00	4.44	0.00	2.22
21	835.00	8.78	1.00	1.00	1.00	1.00	1.00	231.28	24.00	24.00	12.00	35.99	12.00	1.43
22	612.50	10.96	1.00	1.37	1.52	1.00	1.50	47.96	2.49	12.44	0.00	7.46	0.00	2.84
23	575.50	13.30	1.00	1.00	1.00	1.00	1.00	50.30	0.00	7.83	5.22	2.61	7.83	2.92
24	538.50	12.19	1.00	1.00	1.00	1.00	1.00	117.19	12.16	12.16	6.08	18.24	6.08	2.38
25	433.50	7.49	1.00	1.00	1.00	1.00	1.00	36.49	0.00	9.47	0.00	0.00	7.57	3.04
26	404.50	5.69	1.00	1.00	1.00	1.00	1.00	34.69	0.00	9.00	0.00	0.00	7.20	2.91
27	375.50	4.57	1.00	1.00	1.00	1.00	1.00	100.07	31.15	5.19	0.00	0.00	10.38	1.93
28	280.00	2.80	1.00	1.00	1.00	1.00	1.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00
29	282.80	1.73	1.00	1.00	1.00	1.00	1.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	284.53	0.38	1.00	1.00	1.00	1.00	1.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00
31	284.91	1.22	1.02	1.02	1.02	1.02	1.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00
32	286.13	1.82	1.10	1.10	1.10	1.10	1.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33	287.96	0.57	1.00	1.00	1.00	1.00	1.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00
34	288.53	0.00	1.00	1.00	1.00	1.00	1.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00
35	288.53	0.00	1.00	1.00	1.00	1.00	1.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
36	288.53	0.43	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00