Optimal Water Management
– Case Study of Tank Cascade System –

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Background

Competition for water among many users such as industries and domestic water is reducing the amount allocated for agricultural use (irrigation). In addition, water is being contaminated and the quality is deteriorating, while the world population is increasing rapidly. Under these circumstances, it is essential to increase the productivity of water in agriculture, the largest single user of water.

To utilize water effectively, farmers and decision makers need reliable studies based on information. Optimization technique is a promising approach to increase the productivity of water and stabilizing farmers' incomes.

Tank irrigation systems are found in the northern part of Thailand and the southern parts of India and Sri Lanka. They are well suited to small-scale irrigation projects due to the low cost of construction and maintenance. The investment in small scale-irrigation systems such as small tanks from farmers, government and other donors is reportedly high.

In the North Central Province (NCP) of Sri Lanka, tanks (small water reservoirs) provide the main water resource. There are more than 12,000 tanks in NCP. In some cases, the tanks are connected and consist of a continuous system (referred to as "Tank Cascade System (TCS)"). Others function independently. Generally, NCP farmers do not have sufficient rainfall in the dry (Yala) season. During these months, rainfall events tend to be of high intensity and sporadically distributed. Farmers need additional water to obtain adequate yields.

This report focuses on the optimal water management of a tank cascade system (TCS), mainly in the dry (Yala) season. During the wet season (Maha), farmers usually have enough rainfall to cultivate rice, the main and staple crop, while, in the dry season, their rice crop sometimes fails due to water shortage.

The primary objective of this report is to investigate the potential of optimization of water management and the introduction of OFC (Other Field Crops) for crop diversification to raise productivity and stabilize farmers' incomes even during the dry season. In this study, a procedure was developed for determining a cropping strategy to cope with the variations in annual rainfall and surface water inflows in the Meegassagama command area through the use of an optimization model.

Methodology (model description)

There are two seasons - Maha (wet) and Yala (dry) in this region. Generally, there is abundant rainfall in Maha, while the Yala season is drier. Although, the farmers can cultivate rice easily in Maha, it is difficult in Yala. Even if they could plant crops, they might experience drought and lose their investment in Yala. Therefore, our target season was Yala.

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1 Objective function

Objective function is farmer's income. It must be maximized.

$$Be = \sum_{i=1}^{n} Ai * (Yi * Gi - Fi - LCi) + Watval * (St\,(end) - St\,(spec)) \quad (1)$$

Be ; Benefit
n ; Number of crops
i ; Index of crop
Ai ;. Area cultivated to crop *i*
Yi ; Yield of crop *i*
Gi ; Gross margin per unit of production of crop *i*
Fi ; Fixed cost per hectare of crop *i* (such as nutrients and pesticides)
LCi ; Cost of labor per hectare of crop *i*
Watval ; Shadow value of water carried over in reservoir for the next season
St(end) ; Storage carried over to the next season
St(spec) ; Storage specified as the minimum that should be carried over

This is a non-linear equation because *Ai* and *Yi* are both variables and they are multiplied together. The non- linear programming (NLP) procedure is used.

2 Constraints

Water is the largest constraint.

1) Water balance at crop roots

$$Del(m) \geq \sum_{i=1}^{n} Ai * (ETi(m) *(1 - DEFMAXi \,/\, RKYi(m)) + PRESOWi(m) - EFR\,i\,(m)) \quad (2)$$

where *m* is the index for a period, *i* the index for crop.
Del(m) ; Irrigation amount to be delivered for crops in period *m*
ET i(m) ; Water requirement of crop *i* during period *m*
DEFMAXi ; Maximum deficit experienced
RKYi(m) ; Relative yield loss coefficient
PRESOWi(m) ; Water requirement for land preparation and presowing irrigation
EFR i(m) ; Effective rainfall

2) Water balance at the reservoir.

$$St\,(m+1) = St\,(m) + Inflow\,(m) - Del\,(m) * (1/Irrwff) - Resloss\,(m) + AO * EFR\,(m) \quad (3)$$

St (m) ; Storage in reservoir at the beginning of period *m*
Inflow (m) ; Inflow into reservoir during period *m*
Irreff ; Irrigation efficiency(=0.7)
Resloss (m) ; Seepage and percolation loss from the reservoir
AO ; Water spread area of the reservoir
Finally,

$$St\,(end) \geq St\,(spec) \quad (4)$$

3) Labor (Manpower)

Limit on hired labor is represented by the following equation.

$$Pklab * Rellab\,(m) \geq \sum_{i-1}^{n} Hirlabi(m) \quad (5)$$

Pklab ; Labor for hire available during the period of peak labor availability in the season

Rellab (m); Labor for hire availability during period *m* relative to Pklab ((1)

Hirlab i (m) ; Hired labor required by crop *i* during period m.

4) Cultivation extent

$$Toar \geq \sum_{i=1}^{n} Ai \qquad (6)$$

Toar ; Total cultivated area in the command.

Cultivation extent is a natural constraint. The total extent of the command area is 32.5 ha.

5) Yield

$$Yi = Y_0^i * (1\text{-}KYi * DEFMAX\ i) \qquad (7)$$

Y_0^i ; Potential yield of crop *i*

KYi ; Yield loss coefficient (relative yield loss coefficients *RKYi(m)* are given relative to *KYi*).

Yield is a variable. Allowing for deficit irrigation provides the opportunity of using water more efficiently during times of serious shortage.

6) Watval

The concept of value of water (shadow price) at the end of the season is provided. "*Watval*" is the cost for substituting the water.

Input data

Study site (Thirappane TCS) is shown in Fig. 1 and Fig. 2.

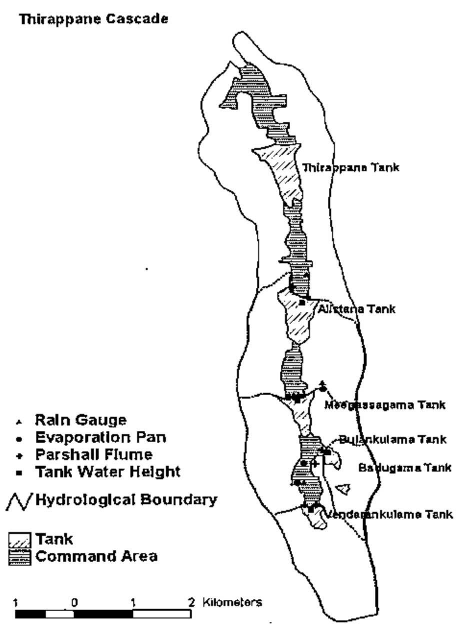

Fig. 1 Thirappane TCS.

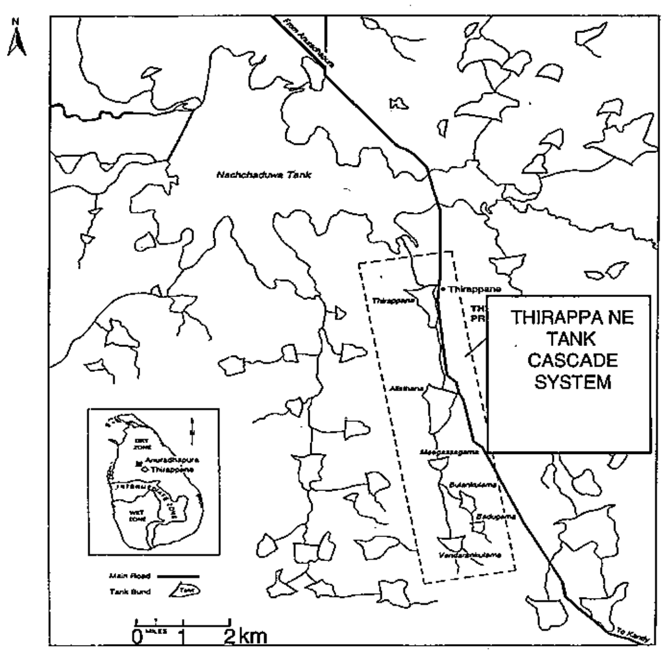

Fig. 2 Site map.

1 Meteorological input

Meteorological data from Maha Illupparama Meteorological Station (8 miles from the cascade) were used for long-term dataset.

2 Hydrological input

Effective rainfall: Effective rainfall (monthly basis) is fixed. About 90% of rainfall is assumed to be effective for rice, while for OFC only 65%.

Inflow: The CASCADE (C.J. Jayatilaka *et al.* (2001)) model, which is a hydrological model of simulation of inflow and seepage loss, was used as inputs to the optimization procedure.

Simulated tank water height and tank water volume on April 1 (at the beginning of Yala season) each year are indicated in Table 1. They depend on the cultivation extent, water management and rainfall in the previous Maha season.

Table 1 Input data 1 (hydrological)

Date	Tank water height (predicted)(m)	Tank volume (predicted)(m^3)
15-Apr-88	2.75	297,182.5
15-Apr-89	0.09	1,549.56
15-Apr-90	2.29	185,294.8
15-Apr-91	2.46	222,584.3
15-Apr-92	0.93	22,691.28
15-Apr-93	0.55	8,491.109
15-Apr-94	2.71	286,030
15-Apr-95	2.71	286,030
15-Apr-96	2.75	297,182.5
15-Apr-97	2.44	217,959

3 Water requirement

Crop water requirement: Pan evaporation is used to estimate the crop water requirement of OFC due to data availability. In other words, the pan evaporation equals the reference crop evapotranspiration (crop coefficient (kc) is assumed to be 1.0 throughout the growing stages), while percolation is also taken into account for the water requirement of rice.

Land preparation requirement: In the Maha season, the farmers do not use water from the tank for land preparation of rice; they wait for adequate rainfall before starting cultivation. In Yala, they usually release water for land preparation (200 mm is a reasonable amount to use for the simulation). They release water for 2 weeks at the end of April.

4 Labor allocation and constraint

The required labor should not exceed the peak labor availability. The unit for manpower is person-day. Availability of family labor is calculated from the number of families (34 families in Meegassagama) and availability of 1.5 person-day of labor per day per family.

5 Crop selection

The preferred staple crop is rice. In the Maha season, almost all the land is covered by rice. In the Yala, the cultivation of rice often results in waste of investment and water because of failure of yield due to drought. The Ministry of Agriculture has recommended the introduction of OFC (Other Field Crops) in theYala season; chili, onion, green gram, cowpea, pigeonpea, gingelly, maize, etc. Among these, chili, maize and onion were selected as target crops, because these crops were already cultivated in the cascade.

6 Cultivation extent

Cultivation extent depends on several factors: soil texture, distance from canals and drainage and land ownership.

There are two types of land allocations: puranawala (first priority area), which is based on historical land ownership, and akkalawela, which is represented by the main lots in the Meegassagama command area. Poorly drained soil is favorable for rice cultivation, while well-drained soil is favorable for the cultivation of OFC.

7 Yield

Potential yield for each crop under full irrigation is estimated from crop economics data (Cost of Cultivation of Agricultural Crops, Department of Agriculture).

8 Crop Economics Data

Other crop economics data were cited from the publications titled:"Cost of Cultivation of Agricultural Crops, Department of Agriculture, Sri Lanka".

Main steps in optimization

The main objective in this section is to propose a strategy for determining the cropping patterns that should be adopted. One item of information that significantly affects the decision is the water availability, particularly during the early period of the season. The amount of water in storage at the start of the season is therefore an important consideration. This was used as a parameter in the determination of optimum cropping patterns for individual years.

The most useful information in determining the cropping patterns is a reliable forecast of rainfall and inflow into the reservoir. However, reliable forecasting is not always possible, even with competent statistical analysis of the data obtained over a large number of years. In the case of very small projects, such as cascade projects, the effort required for developing a good "forecast model" would not be justified, nor are adequate data likely to be available. Instead, it would be preferable to design a strategy from studies of what could have been done over a historical period for which data are available or can be generated from primary data. For the project area under study, an inflow series for the historical 10-year period 1988 to 1997 has been generated by applying the CASCADE model constructed by Jayatilaka *et al.,* 2001.

Results and discussion

The NLP formulation determines the optimum cropping pattern considering the resources available in that year. The resources include initial storage, maximum hired labor that could be used, and the net inflow in that year as computed by the CASCADE model.

1 Individual year optimization run

Table 2 shows the optimization runs under both formulations of farmer labor. The area irrigated varied from year to year, for any level of initial storage. A cropping strategy for that level of initial storage was deduced from visual examination of the optimal cropping mixtures.

Figs. 3 and 4 show the relationship between the probability and crop coverage for rice and OFC, respectively. These were ranked based on hired labor =500. The probability refers to the chance of obtaining yield. The probability of rice decreased with the increase of the crop cover. The exact relationship could not be

Table 2 Example of calculation (hired labor limit=500)

	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Op=10,000										
Rice	6.13	6.13		7.40	6.34	6.13		7.78	10.04	11.64
		0.27		0.19	0.18	0.21			0.24	
Chili	3.75									
Onion_1	1.95	3.11								
Onion_2	5.64	6.10								
Op=50,000										
Rice	6.13	6.13	6.13	6.91	6.31	6.13		7.78	9.28	11.64
		0.08	0.04			0.02			0.08	
Chili	3.75									
Onion_1	1.95	3.11	3.11							
Onion_2	5.64	6.10	6.10							
Op=90,000										
Rice	6.13	6.13	6.13	8.97	8.40	7.95		7.78	11.03	11.64
									0.05	
Chili	3.75	3.75								
Onion_1	1.95	1.95	3.11							
Onion_2	5.64	5.64	6.10							
Op=170,000										
Rice	6.13	6.13	6.13	13.09	12.57	12.02	6.13	7.78	14.53	11.64
							0.04			
Chili	3.75	3.75								
Onion_1	1.95	1.95	3.11							
Onion_2	5.64	5.64	6.10							
Op=210,000										
Rice	6.13	6.13	6.13	14.78	14.65	14.06	6.61	7.78	15.29	11.64
Chili	3.75	3.75								
Onion_1	1.95	1.95	3.11							
Onion_2	5.64	5.64	6.10							
Op=250,000										
Rice	6.13	6.13	6.13	14.78	16.74	16.10	6.61	7.78	15.29	11.64
Chili	3.75	3.75								
Onion_1	1.95	1.95	3.11							
Onion_2	5.64	5.64	6.10							

deduced due to the shortage of data. However, the probability decreased markedly for a rice crop cover of 20%. The probability for rice was also affected by the initial storage. The probability increased with the increase of the initial storage, while, the probability of OFC decreased more along with the increase of crop coverage. The difference between the initial storage and crop coverage was negligible.

These results suggest that labor is the main restriction for a higher coverage of OFC (Other Field Crops). On this basis, the optimal cropping mixture can be determined with a probability of around 70 or 80 % for the specific conditions.

2 Crop strategy

The strategy must take into consideration the type and level of risk that the farmer would find acceptable. One way of characterizing the risk is to calculate the number of years during which it would have

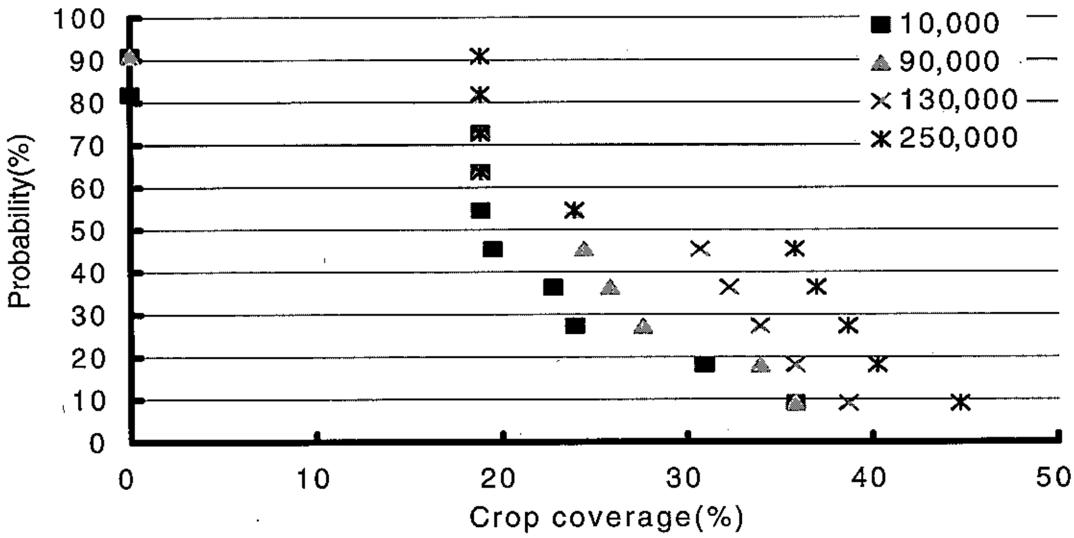

Fig. 3 **Probability (rice, labor=500).**

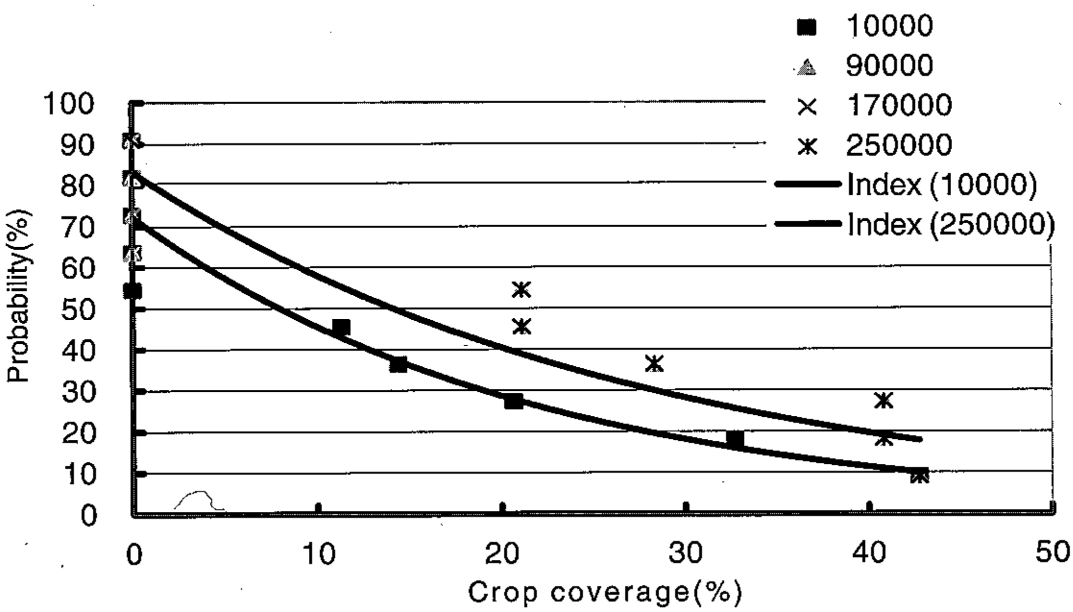

Fig. 4 **Probability (OFC, Labor=500).**

been possible to successfully develop a given cropping pattern, for any particular set of values based on the initial storage and hired labor availability. The cropping pattern, to be repeated every year, will be determined from the relevant cropping strategy, for example, assuming that failure of the crops can be tolerated only in one year out of ten. The acceptable cropping patterns can be deduced from the examination of the Table, for various values of initial storage.

The NLP formulation itself can be used for the simulation run; the crops to be grown will not be variables to be determined by the NLP, but will be given values taken from the strategy Table. Results of such a simulation are presented to show the variation in the value of the objective function from year to year.

The return that the chosen strategy yields must be compared with the returns that were obtained with the original optimization runs. It will be seen that in many years the return will be much smaller than could have been obtained if the optimal cropping for that year had been adopted.

The step of deducing a strategy by visual examination is a weak point in the methodology, because the application is difficult. It would be preferable if a formal methodology could be prescribed. This is provided by what is known as the maxmin approach.

The maxmin approach requires that the objective function maximize the minimum return that occurs. A less rigorous approach can be obtained by dropping the worst year out of the set of years. The program will determine the cropping pattern that will have to be adopted every year for a given initial storage and hired labor availability, so that the minimum return obtained over the years is maximized.

Table 3 shows the simulation results of one cropping strategy. In Table 3, the simulated return varies with the years and initial storage. For labor availability 300, there is sometimes a ceiling value because labor is the main constraint, while for labor availability 500, the return increases with the increase of the initial storage. A negligible increase of return can be seen for labor constraint in the case of a smaller initial storage, while some increase can be seen in the case of a larger initial storage. In Table 3, cropping strategies depend

Table 3 Simulation results

Return with labor availability at 300										
	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
10,000	235.5	86.8		70.5	57.4	36.5		131.1	171.5	173.4
50,000	240.1	136.9	169.6	124.3	112.2	97.7		135.5	212.3	178.0
90,000	253.9	165.6	198.2	159.6	159.1	151.5		138.0	241.7	191.7
130,000	258.8	186.5	219.0	180.3	179.7	172.2		139.8	262.6	196.5
170,000	258.8	202.5	235.0	190.0	195.7	188.2	132.8	139.8	271.8	196.5
210,000	258.8	218.5	237.4	190.0	211.7	204.2	159.3	139.8	271.8	196.5
250,000	258.8	234.5	237.4	190.0	225.6	220.2	159.3	139.8	271.8	196.5

Return with labor availability at 500										
	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
10,000	235.5	86.8		70.5	57.4	36.5		131.1	171.5	173.4
50,000	240.1	136.9	169.6	124.3	112.2	97.7		135.5	212.3	178.0
90,000	253.9	165.6	198.2	159.6	159.1	151.5		138.0	241.7	191.7
130,000	265.6	192.7	225.4	186.3	185.7	178.1		121.5	268.9	203.4
170,000	269.6	212.3	245.0	204.6	205.0	197.2	83.2	98.9	288.4	207.6
210,000	271.6	230.0	251.7	207.7	222.7	214.7	117.7	87.7	290.6	209.7
250,000	273.7	247.8	254.1	210.8	239.7	232.3	108.4	76.4	292.7	211.8

on the initial storage and labor availability. Rice cultivation increases due to the increase in labor availability, while no increase can be seen for OFC cultivation.

Table 4 presents the crop plans recommended in the minmax solutions over the range of initial storage and hired labor availability tested. These should be compared with the individual solutions presented earlier, and what an evaluation made of those that could be adopted with reasonable risk.

If a crop decision could be made a few weeks after the start of the season, the storage in the reservoir at that time and inflows in the intervening weeks could give a useful indication of the hydrological year, and a decision on how much area could be assigned to the later crop would be based on this information.

Table 4 Simulation results

Decision							
	Cropstrat (c,z,w) Crop strategy – Cropping pattern at initial storage						
	0.0	1.0	2.0	3.0	4.0	5.0	6.0
Rice	6.13	6.13	6.13	6.13	6.13	6.13	6.13
Maize	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chili	0.00	0.50	2.00	2.00	2.00	2.00	2.00
Onion_1	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Onion_2	3.00	3.00	3.00	3.30	3.30	3.30	3.30
+	0.1	1.1	2.1	3.1	4.1	5.1	6.1
Rice	6.13	6.13	6.13	7.00	8.00	8.50	9.00
Maize	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chili	0.00	0.50	2.00	2.00	2.00	2.00	2.00
Onion_1	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Onion_2	3.00	3.00	3.00	3.50	3.50	3.50	3.50

	Initial storage index z						
z	0	1	2	3	4	5	6
Storage(m^3)	10,000	50,000	90,000	130,000	170,000	210,000	250,000

	Labor availability index w (person-day per half-month)	
w	0	1
Labor force	300	500

Conclusion

The main objective of this study was to develop a procedure for determining a cropping strategy within the context of variations in annual availability of rainfall and surface water inflows, through the use of an optimization model.

The effects of the major components have been discussed, including the impact of the initial storage and labor availability as these affect the net return and cropping mixture. The main conclusions derived are as follows:

1) Optimal cropping mixture could be selected, subject to specification of a conservative response to risk. Simulations can be carried out to evaluate the decision strategy. The initial storage exerts a considerable effect on the cropping mixture and net return in Yala. This fact suggests that it is important to manage the

water in Maha in considering the effect on the end of season storage, if the objective is to raise productivity and income in the following Yala season.

2) Labor availability is another important determinant. Labor should be arranged properly to increase productivity.
3) The cropping strategy simulation was carried out with a long series of data. The feasibility check was performed. And evaluation of the outcome of the simulation by applying a methodology for decision-making under risk was carried out. Satisfactory results were derived.

These techniques enable farmers and decision-makers to improve water management decisions, easily.

Reference

Jayatilaka, C. J., Saktivadivel, R., Shinogi,Y., Makin, I. W. and Witharana, P. (2001): Predicting Water Availability in Irrigation Tank Cascade System: The *CASCADE* Water Balance Model. IWMI Research Report No. 48.