J. Indian Water Resour. Soc.,
Vol. 39, No. 4, Oct., 2019

OPTIMIZATION OF OPERATION SCHEDULE OF RESERVOIR FOR IRRIGATION USING HARMONY SEARCH ALGORITHM – A CASE STUDY

Abhay Kumar Jha[1], Sandeep. M . Narulkar[2] and Saleem Akhtar[3]

ABSTRACT

In many of the countries irrigated agriculture is considered to be the main culprit of water scarcity because of mismanagement. Judicious use of water to maximize the crop productionis the key for management. This is achieved through system analysis and optimization. In most of the non-perennial rivers the reservoirs play a vital role in management of water. Creation of a reservoir is a costly affair hence is to be planned and operated optimally to achieve maximum gains. The irrigation reservoirs have emphasis on maximization of the crop yield in its commanded area. For the optimal operation lots of mathematical programming techniques are in practice. In recent times meta-heuristic techniques for optimization have become popular. Harmony Search Algorithm (HSA) is also a meta-heuristic optimization technique and has been used effectively in reservoir problems. The main purpose of the paper is to demonstrate the potential of HSA to optimize regulation policy that distributes the water stored in the reservoir optimally in various fortnights amongst different crops. An irrigation reservoir in Central India to maximize the crop yield in dry weather season was chosen in this study.

.***Keywords:*** *Water Resources System, Reservoir, Optimal Operation, Harmony Search Algorithm, Crop Yield.*

INTRODUCTION

World Resource Institute (2015) estimated that 54 % of the country's area faces extreme water stress due to over utilization of the available resources. Irrigation consumes maximum fresh water resources (70 to 90%) in developing countries and is considered to be the main culprit of water scarcity. The reason is wasteful use of water due to mismanagement. India is not an exception. Water scarcity is looming large in India where agriculture sector consumes 78 per cent of water. According to the Central Water Commission (CWC, 2014), by 2050 the total water demand will overshoot supply in the country and the share of irrigation will come down to 68 %. According to Planning Commission Government of India (2009) efforts are required to be made so that irrigation efficiency will increase to 60% from the present level of 35 to 40%. Judicious use of water to maximize the crop production is the key for management. India has a large number of non perennial rivers which have seasonal flows. The wet weather flow is around 80 to 90 percent of the total annual flow which needs storage and thus there are many reservoirs in India. Most of them are meant for irrigation as a major purpose. The irrigation reservoirs must have a mandate on maximization of the crop yield in its commanded area. Hence, improving water use efficiency should be crucial.

Creation of a reservoir is a costly affair hence is to be planned and operated judiciously and optimally to achieve maximum gains. For the optimal planning and operation of the reservoirs mathematical programming techniques have been in practice since decades. Till nineties mostly the methods of operation research viz. the Linear Programming, Dynamic Programming and Non Linear Programming and their combinations and variants were in vogue. These techniques solved problems of specific nature to obtain global optimum. However, in reality the problems are extreme non-linear and complex which preclude obtaining global optima. In recent years, various meta-heuristic techniques have also been used to solve reservoir operation optimization problems. The word 'heuristic' is defined in the context of computing as a method of denoting a rule-of-thumb for solving a problem without the exhaustive application of a procedure (Bandaru and Deb, 2016). The techniques also have limitations regarding its universal applications. To address this Meta-heuristic optimization techniques based on iterative simulations have been introduced, allowing appropriate solutions to be found using limited computation time and memory and without requiring any complex derivatives. (Yoo and Kim, 2014) Most Meta-heuristic methods are motivated by natural, physical or biological principles and try to mimic them at a fundamental level through various operators, (Bandaru and Deb, 2016). An extensive review of Meta-heuristic algorithms presented by Bandaru and Deb (2016) and their applications to hydrological sciences is presented in the work of Yoo and Kim (2014). Present work is based on an application of a Meta-heuristic Technique namely the Harmony Search Algorithm (HSA) to reservoir operation studies. This is an interesting algorithm which was first developed by Geem et al. (2001). The basic premise of HSA was to correlate the search of the harmony in music to the point of optimality in an optimization process. Both the processes intend to produce the best or optimum. Though it is a relatively new Meta-heuristic algorithm, its effectiveness and advantages have been demonstrated in various applications. Geem (2007) applied HSA to the optimal operation scheduling of a multiple dam system to

1. *Research Scholar, RGPV, Bhopal*
2. *Professor, Civil Engineering, SGSITS, Indore*
3. *Professor, Civil Engineering, UIT, RGPV, Bhopal*
Email: abhaykumarjha0907@gmail.com
Manuscript No. 1529

generate five different global optimal solutions with identical maximum benefit from hydropower generation and irrigation. Yang (2009) analyzed the power of new HSA in the context of meta-heuristic algorithms.Kougias and Theodossiou (2013) applied HSA using Visual-Basic and MATLAB platform to solve classic dam scheduling problem of optimizing the operationof a four-reservoir system over 24 hours Atrabi et al. (2015) solved HSA for reservoir operation optimization during flood.

Present study is aimed at establishing a procedure for optimum utilization of water for irrigation purpose at Samrat Ashok Sagar Reservoir (SASR) (popularly known as Halali Dam) in the District of Vidisha in the state of Madhya Pradesh. The reservoir is meant for irrigation of the crops in lean period in which the inflow to the reservoir is negligible. The available storage created through the flows in wet season has to support multiple crops in the lean season. In the present study HAS is adopted for optimization of irrigation over a period amongst various crops with an aim of maximizing the crop production. The specific objective of the study is to maximize the yield and to allocate water in a multi-crop and multi-seasonal environment. The problem is solved in three stages. First fortnightly crop water requirement are calculated secondly allocation of water is made through HSA optimization.

METHODOLOGY

On the basis of study of the literature reviewed in the foregoing discussion the present study has been framed. The details are presented below:

Demand Computation

For calculating water requirement and the corresponding crop yield one has to investigate the crop-soil-water-atmosphere system. The major consumptive use of water the Evapo-Transpiration (ET) estimated as standard Reference Evapo-Transpiration (RET) is calculated first by application of CROPWAT-8.0 Software mentioned in FAO-56 (1998). The software uses inputs related to climatic conditions, geographic information, soil characteristics, and water quality at the region of interest. The software assumes that all other input factors to crop yield (such as pesticides, know-how, seeds etc.) are kept at their optimal levels. The RET value for the project area for i^{th} season (RET^i) has been worked out using Penman Monteith Method. (Equation 1)

$$RET^i = \frac{0.408\,\Delta\,(R_n - G) + \Upsilon \frac{900}{T+273} u_2\,(e_s - e_a)}{\Delta + \Upsilon\,(1 + 0.34\,u_2)} \qquad (1)$$

Where: RET^i = the reference evapo-transpiration [mm / day] in i^{th} fortnight; R_n = net radiation received at the crop surface [MJ m^{-2} day^{-1}], G = the soil heat flux density [MJ m^{-2} day^{-1}], T = the mean daily air temperature at 2 m height [°C], u_2 = wind speed at 2 m height [m s^{-1}], e_s = saturation vapour pressure [kPa] at T [°C], e_a = actual vapour pressure [kPa], Δ = slope of vapour pressure curve [kPa $°C^{-1}$], γ = the psychrometric constant [kPa $°C^{-1}$]. For the various crops sown in an area the crop evapo-transpiration is required to assess the water requirement of individual crops in different seasons.

Potential evapotranspiration

The Potential Evapo-Transpiration (PET) is calculated for the various crops sown in the command area of SASR canal system for various seasons *i*. The RET values computed from Equation 1 were multiplied by the crop coefficient to get the *PET* values (Equation 2).

$$PET_c^i = k_c^i * RET^i \qquad (2)$$

k_c^i = the crop coefficient for c^{th} crop in i^{th} fortnight; PET_c^i values is the potential evapo-transpiration value for c^{th} crop in i^{th} fortnight This value is considered as demand for each crop in each of the seasons.

Optimization

For optimization the Harmony Search algorithm is used in the present study. The flow chart of optimization process using HSA is given in Figure 1.

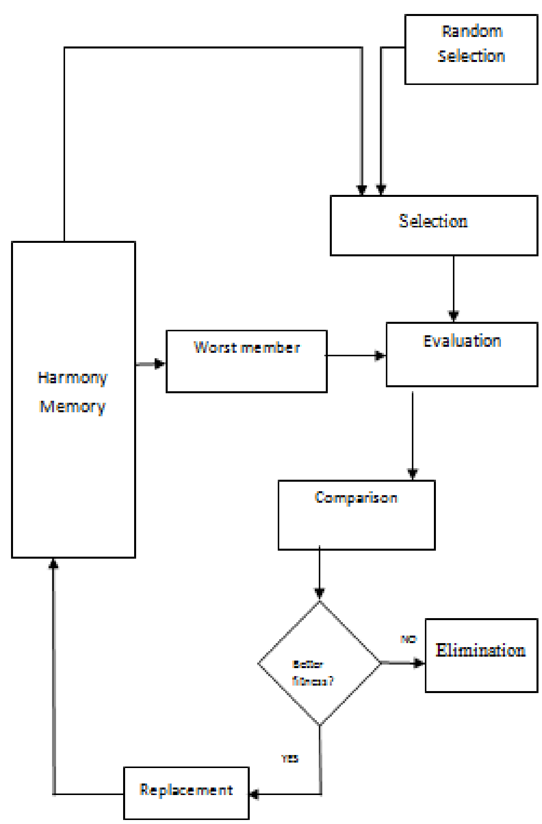


Figure 1: Flow Chart of Harmony Search Algorithm

MODEL DEVELOPMENT

The formulation of the reservoir operation optimization problem for the SASR has been carried out considering two objective functions. One is additive function and other is multiplicative function. The first objective function is minimization of the sum of the squared deviation of irrigation demand and supply deficits in each season and for all the crops. This is added with the squared derivation of the storage balance equation (Equation 3).

$$\boldsymbol{min\ f(x)} = \sum_{nc=1}^{NC}\sum_{t=1}^{N} ky_t^{nc}\left(R_{t,nc} - D_{t,nc}\right)^2 + \sum_{t=1}^{N}\left(S_t\,(1 - B * e_t) - S_{t+1}(1 + B * e_t) + I_t - \sum_{nc=1}^{NC} R_{t,nc} - A_o * e_t\right)^2 \quad (3)$$

The second objective function is sum for all the crops of product of the square deviation of releases and demands for a single crop for all the seasons added by the squared deviation of the storage balance equation.

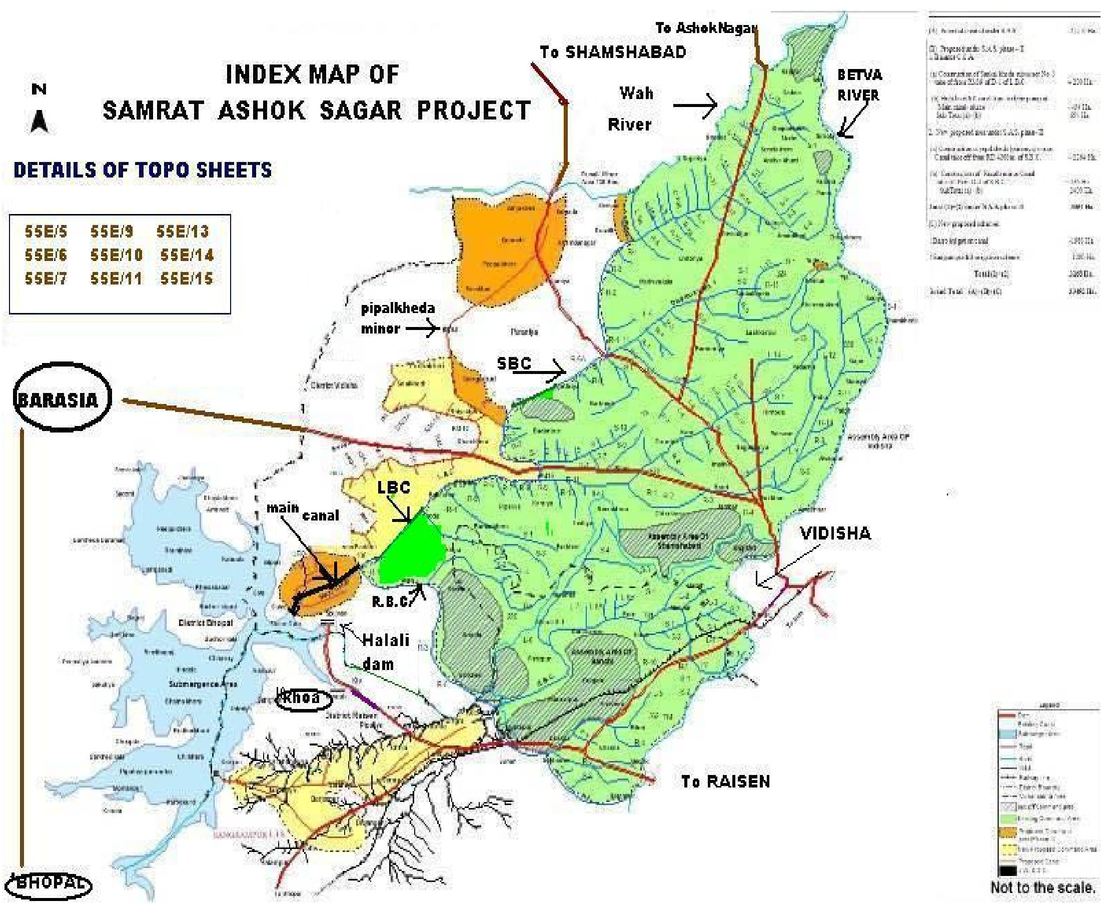
$$\boldsymbol{min\ f(x)} = \sum_{nc=1}^{NC}\prod_{t=1}^{N} ky_t^{nc}\left(R_{t,nc} - D_{t,nc}\right)^2 + \sum_{t=1}^{N}\left(S_t(1 - B * e_t) - S_{t+1}(1 + B * e_t) + I_t - \sum_{nc=1}^{NC} R_{t,nc} - A_o * e_t\right)^2 \quad (4)$$

$R_{t,nc}$ = release in the period $t = 1, 2..., N$ for crop $nc = 1, 2, ..., NC$ (MCM), $D_{t,nc}$ = demand to sustain the crop $nc = 1,2,..., NC$ in the period $t=1, 2..., T$ (MCM), ky_t^{nc}= yield response factor for time period $t= 1, 2..., N$ of crop $nc = 1, 2..., NC$, S_t = Storage at time period $t= 1, 2..., N$ (MCM), S_{t+1}= Storage at time period $t+1$ (MCM), I_t = Inflow at time period $t= 1, 2..., N$ (MCM), A_o and B = Regression constant correlating surface area (Ha) and storage value, e_t= Rate of evaporation at each fortnight in (mm) .

Two different problems are formulated and solved. The first objective function is very commonly adopted type but it is not realistic one. The second function is very rarely been adopted for optimization but is realistic in the sense of crop yield reduction. Both these formulations are subjected to following constraints.

Irrigation Demand Constraints

The releases for irrigation should be more than or equal to zero to sustain the crops and also at the same time this should not exceed the maximum irrigation demand to produce the targeted yield (Equation 5).



Source: SMP_SAS_WRD Vidisha_20_03_12

$$0 \le R_{t,nc} \le D_{t,nc} \quad (5)$$

$R_{t,nc}$ = release in the period $t = 1, 2..., N$ for crop $nc = 1, 2, ..., NC$ (MCM), $D_{t,nc}$ = demand to sustain the crop $nc = 1,2,..., NC$ in the period $t=1, 2..., T$ (MCM),

Reservoir Storage – Capacity Constraints

The reservoir storage (S_t) in each fortnight should not be less than the dead storage, and should not be more than the live storage of the reservoir (Equation 6).

$$S_{min} \le S_t \le S_{max} \quad (6)$$

S_{min} = Dead Storage of the reservoir in MCM,. S_{max} = Maximum Capacity of the reservoir in MCM.

Data Collection and Analysis

The data for the analysis was collected from various sources. The data regarding the cropping pattern and physical aspects of the reservoir were collected from the Central Water Commission (2006), visiting the dam site and various state level offices of M.P. Water Resources Departments in Bhopal and IMD website, Water Portal website etc. The Rabi Season irrigation is considered in the present problem and the cropping pattern is presented in Table 1. The monsoon season in India is uncertain and has a direct effect on the runoff to the reservoir which may lead to variation in filling levels of the reservoirs. In all 6 different levels of initial storage in the reservoir have been taken to analyze the problem in the present study. They are 226.9 (full storage), 204.21, 181.52, 158.53, 136.14 and 113.45 MCM. The total command area is 37419 Ha and the area to be covered by the reservoir system is 86.30% that is approximately 32292 Ha. The Crop calendar adopted for the present study is shown in Table 2. The adopted reference crop evapotranspiration values are shown in Table 3.

Table 1. Cropping Patterns in the Case Study for Rabi Season

S. No.	CROP	% AREA	AREA (Ha)
1	GRAM	7	2400
2	MOONG	2	600
3	VEGETABLE	0.7	292
4	WHEAT	90	28900
5	BARSEEM	0.3	100
	TOTAL	100	32,292

Table 2. The Crop Calendar Adopted

S. No.	CROP	TIME DURATION	DAYS
1	GRAM	16 OCT - 28 FEB	135
2	MOONG	15 FEB – 15 APR	60
3	VEGETAB	1 NOV – 31 JAN	90
4	WHEAT	16 NOV – 15 MAR	120
5	BARSEEM	16 OCT - 15 FEB	120

Table.3 Reference Evapotranspiration Values

FORTNIGHT	TIME DURATION	ETo (mm)
1	16-31 OCT	53.98
2	1-15 NOV	48.95
3	16- 31 NOV	40.04
4	1-15 DEC	40.00
5	16-31 DEC	40.00
6	1-15 JAN	40.04
7	16- 31 JAN	49.00
8	1-15 FEB	51.82
9	16- 28 FEB	56.13
10	1-15 MAR	85.72

RESULTS

The models explained in the foregoing discussions have been implemented with the data of SASR for Rabi Season Irrigation. The results of the applications of the model are presented in the following paragraphs along with the discussions.

Computation of demand of water

The computation of fortnight wise RET values using the CROPWAT 8.0 Software are carried out using the local climatic data. Further, the results for computations for PET for each crop in various fortnights and the subsequent demands are presented in Table 4.

Results of releases at various initial storages

The Addition and Multiplication models were applied to the problem as per the formulation explained. The actual demands, the computed releases from the Addition Model and the Multiplication Model in each of the fortnight for different initial storage of reservoir are computed and are presented in Figures 2 to 7.

Computations of final relative yield ratios for different initial storages

The present problem is solved using the HSA model is applied to various crops to optimize water allocation to maximize the yield. The original optimization models were resulting in to the level of demand fulfillment. These volumes computed from the results were then used in a crop-water simulation model to determine the relative yield ratios in various fortnights and the final relative yield ratios. The objective of the present study was to maximize the yield ratios for all the crops that is to maximize the production. The releases computed from the optimization model for different crops in different fortnights for various levels of initial storage values in the reservoir are used to compute the depth of water supplied to the crop by dividing the total volume by the crop area and appropriate conversion factor. Then a soil moisture simulation model (Equation 7) was applied to each of the crops. The

Table 4: Computation of Fortnightly Demand for Gram

SOWING DATE	16-Oct	Crop	Gram	Area Sown	2400 (Ha)	Demand	
DAYS	FORT NIGHT	ET_o (mm)	Kc	Growth STAGE	PET=Kc*ET_o (mm)	Million Cubic Meters (MCM)	Mm
15	1	53.98	0.23	ini	12.4154	0.358	14.898
30	2	48.95	0.28	devp	13.706	0.395	16.447
45	3	40.04	0.69	devp	27.6276	0.796	33.153
60	4	40.00	1.02	devp	40.8	1.180	48.96
75	5	40.00	1.05	devp	42	1.210	50.4
90	6	40.04	1.04	mid	41.6416	1.199	49.970
105	7	49.00	0.89	mid	43.61	1.256	25.332
120	8	51.82	0.63	mid	32.6466	0.940	39.176
135	9	56.13	0.41	end	23.0133	0.663	27.616

procedure comprises of solving three equations (Equations 7 to 9) at each time steps to solve for the Actual Evapo-transpiration and the soil moisture storage in the root zone of each crop in various time periods. The relative yield is computed as per the Equation 10.

$$SM_{t+1} * Z_{t+1} = SM_t * Z_t + R_t + X_t + S_o(Z_{t+1} - Z_t) - AET_t \quad (7)$$

$$Z_t = Z_{max}\left[0.5 + 0.5\, sin\left\{3.03\left(\frac{t}{t_{max}}\right) - 1.47\right\}\right] \quad (8)$$

$$AETt = \begin{cases} 0;\ SMt \le WPt \\ \frac{PETt\,(SM_t - WP)}{(1-p)(FC-WP)};\ WP < SM_t \le (1-p)\,(FC - WP) \\ PETt;\ SMt \ge (1-p)(FC - WP) \end{cases} \quad (9)$$

$$R_t^*(X_t, AET_t) = 1 - ky_t^{nc}\left(1 - \frac{AET}{PET}\right)_t \quad (10)$$

Where, Z_t and Z_{t+1} are root zone depths in the periods t and t+1 respectively, (cm), R_t is the rainfall in the period t (mm), X_t is the water depth allocated in period t (mm), S_o is the initial soil moisture content in the extended root zone (mm/cm), t_{max} is the time for the full development of root zone (days), Z_{max} is the maximum possible depth of effective root zone, ky_t^{nc} is the yield factor for period t of the crop nc, AET is the actual evapo-transpiration (mm) and PET is the potential evapo-transpiration for the crop *nc* in time *t*, SM_t and SM_{t+1} are the soil moisture content in depth units per unit root depth in period t (mm/cm), FC = Field capacity (mm/cm), WP = Wilting point (mm/cm), p = Crop water depletion fraction.

The root depth values for various crops are computed using the model presented in Equation 8. Since this was a prerequisite for assessment of soil moisture and actual evapotranspiration using Equations 7 and 9. The results have been shown in Table 5 for Gram. For all other crops the results have and are considered in the study.

The Equations 7, 9 and 10 are applied to the data to compute the soil moisture storage for different crops in different fortnight along with actual evapotranspiration and to compute the relative yields for each of the crops under different initial storage conditions. The results of final yields for various crops at different storage level using both the models have been presented in Table 6 and Figures 8 to 12.

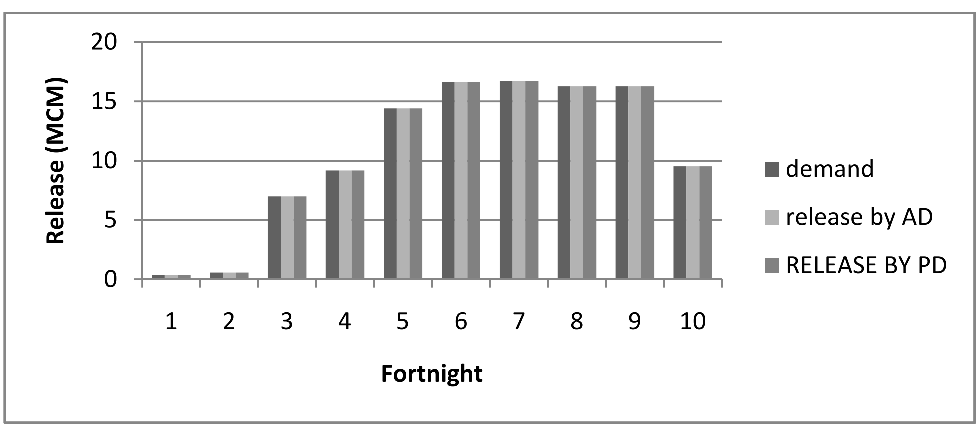


Fig.2: Fortnightly Demand vs Release from Initial Storage 226.90 MCM as per HSA

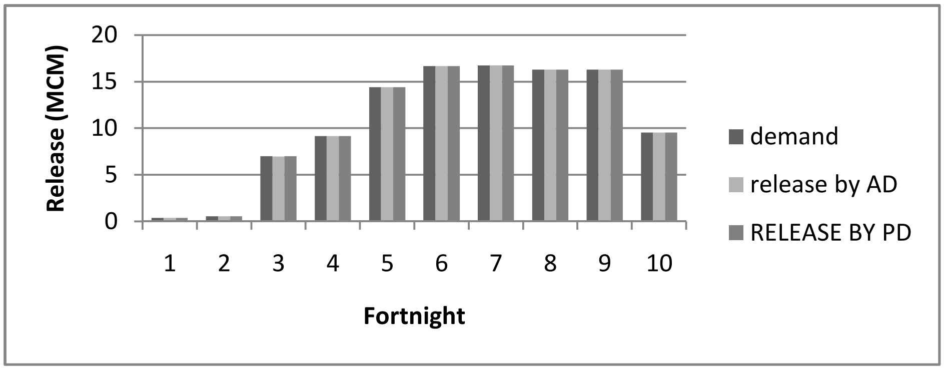


Fig.3: Fortnightly Demand vs Release from Initial Storage 204.21 MCM as per HSA

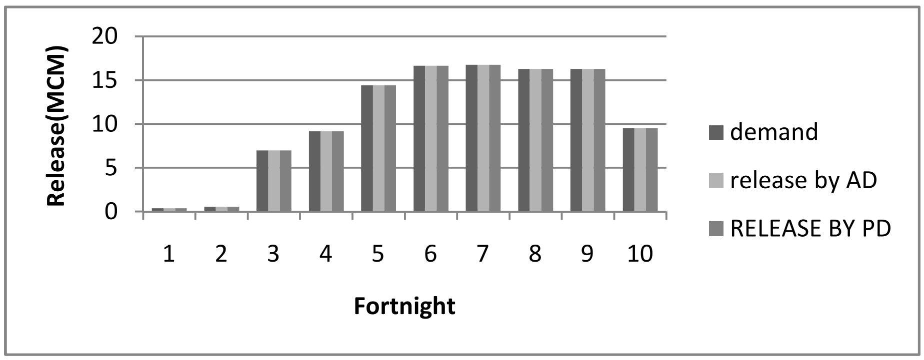


Fig.4: Fortnightly Demand vs Release from Initial Storage 181.52 MCM as per HSA

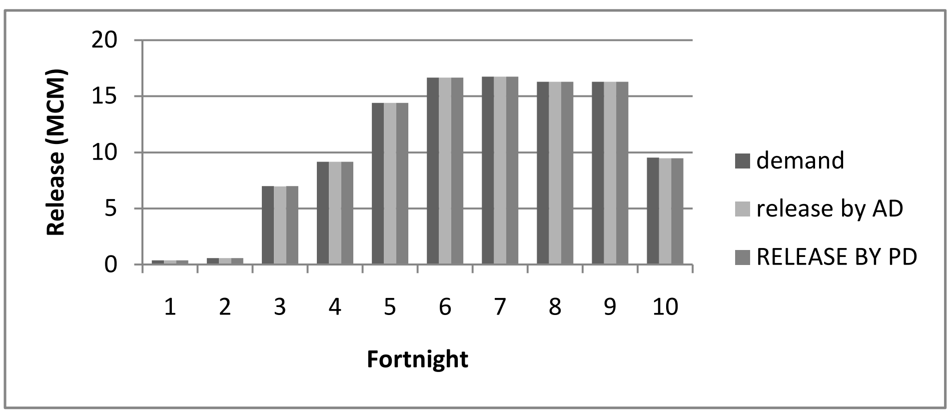


Fig.5: Fortnightly Demand vs Release from Initial Storage 158.53 MCM as per HSA

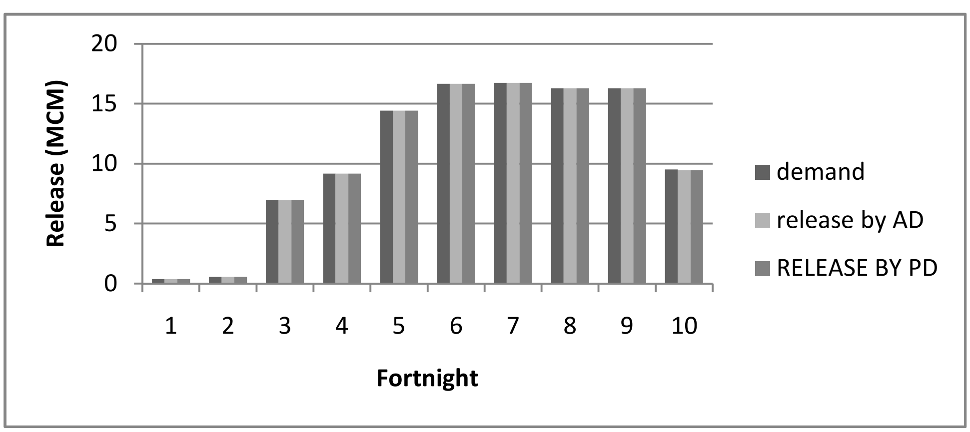


Fig.6: Fortnightly Demand vs Release from Initial Storage 136.14 MCM as per HSA

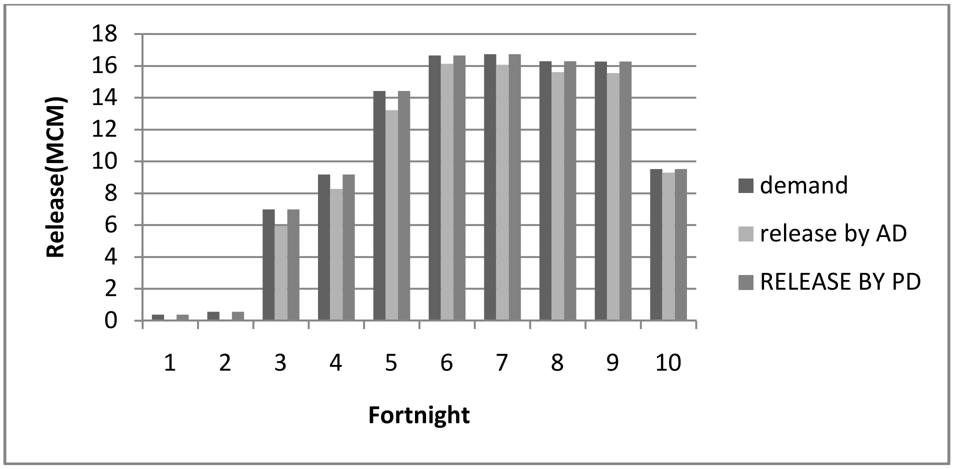


Fig.7: Fortnightly Demand vs Release from Initial Storage 113.45 MCM as per HSA

Table 5: Computation of Fortnightly Root Depth Values for Gram

Fortnight	Time Period (t days)	Root Depth (Zt cm)
OCT II	15.000	13.346
NOV I	30.000	41.704
NOV II	45.000	78.374
DEC I	60.000	114.202
DEC II	75.000	140.243
JAN I	90.000	149.996
JAN II	105.000	141.026
FEB I	120.000	115.573
FEB II	135.000	79.991

Table 6: Final yield for Gram by Addition function and Product function

	Storage	Relative Yield by Addition Function	Relative Yield by Product Function
Gram	226.9	1.000	1.000
	204.21	1.000	1.000
	181.52	1.000	1.000
	158.83	1.000	1.000
	136.14	1.000	1.000
	113.45	0.993	1.000
Barseem	226.9	1.000	1.000
	204.21	1.000	1.000
	181.52	1.000	1.000
	158.83	1.000	1.000
	136.14	1.000	1.000
	113.45	0.927	1.000
Moong	226.9	1.000	1.000
	204.21	1.000	1.000
	181.52	1.000	1.000
	158.83	1.000	1.000
	136.14	1.000	1.000
	113.45	0.898	1.000

Vegetable	226.9	1.000	1.000
	204.21	1.000	1.000
	181.52	1.000	1.000
	158.83	1.000	1.000
	136.14	1.000	1.000
	113.45	0.937	1.000
Wheat	226.9	1.000	1.000
	204.21	1.000	1.000
	181.52	1.000	1.000
	158.83	1.000	1.000
	136.14	1.000	1.000
	113.45	1.000	1.000

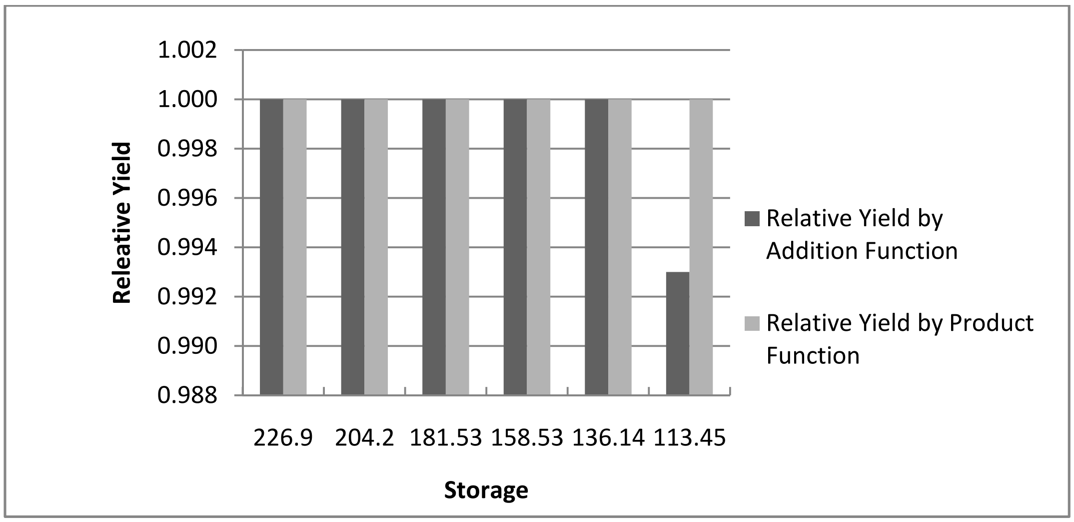


Figure 8: Relative Yield for Gram at Different Storage Levels

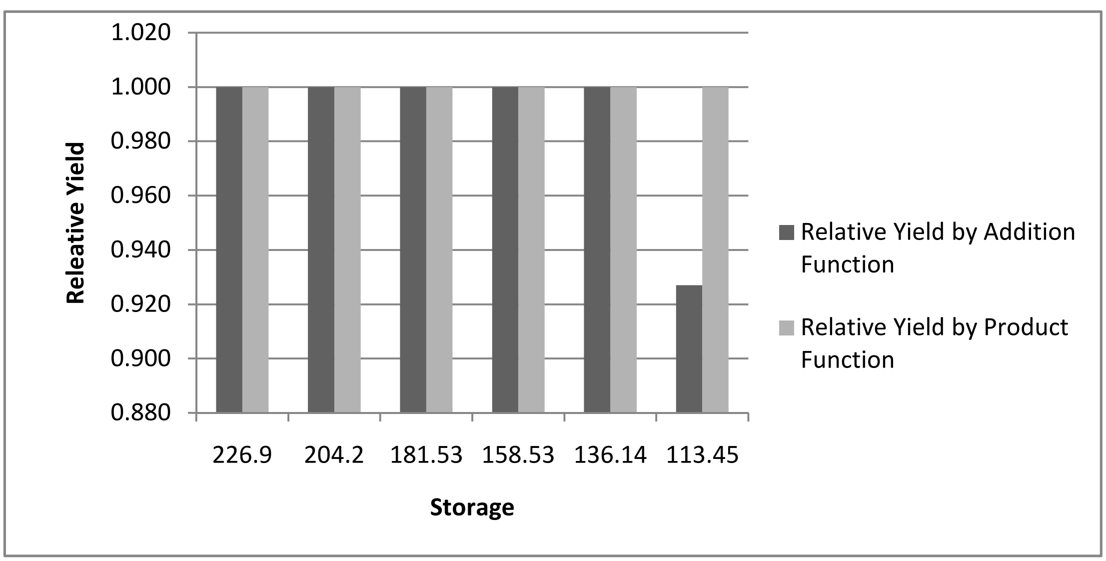


Figure 9: Relative Yield for Barseem at Different Storage Levels

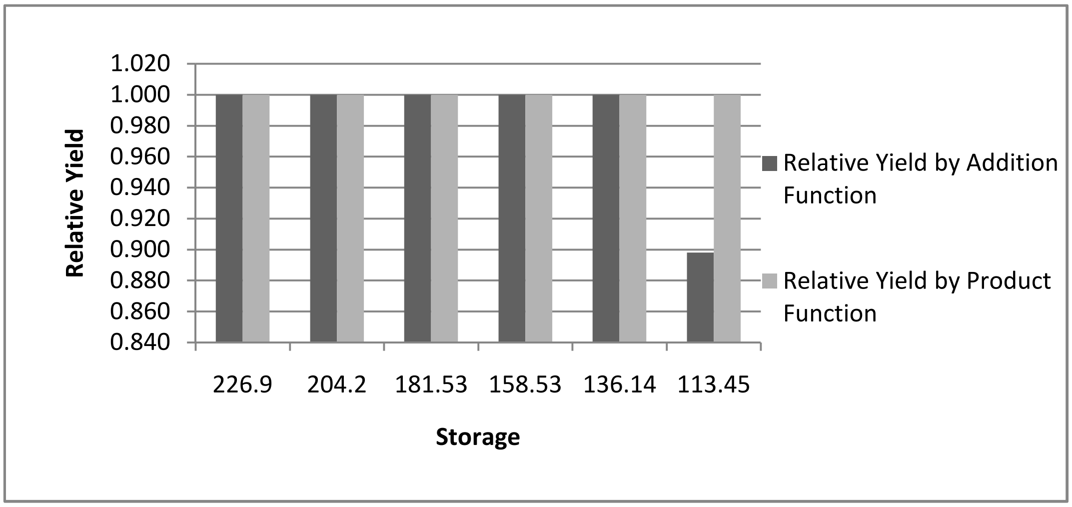


Figure 10: Relative Yield for Moong at Different Storage Levels

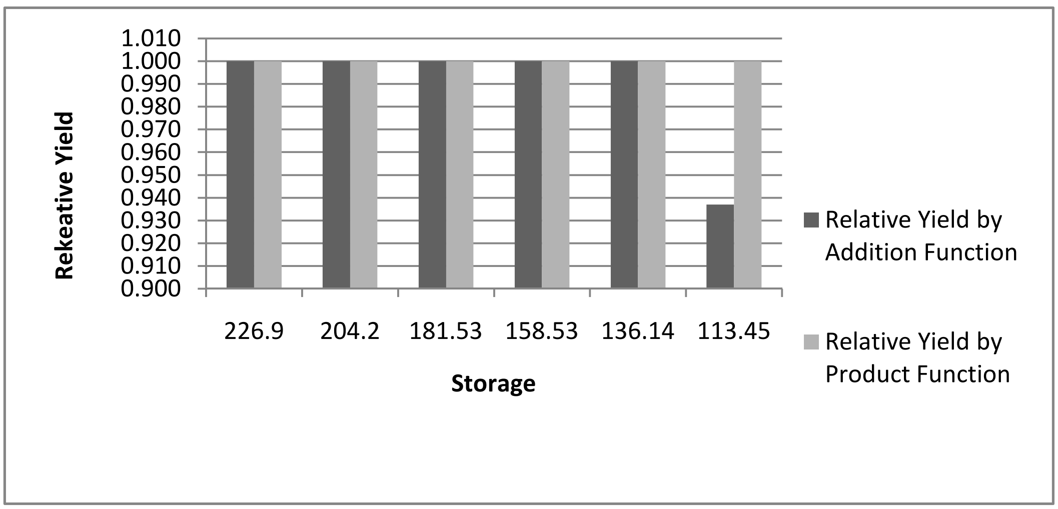


Figure 11: Relative Yield for Vegetables at Different Storage Levels

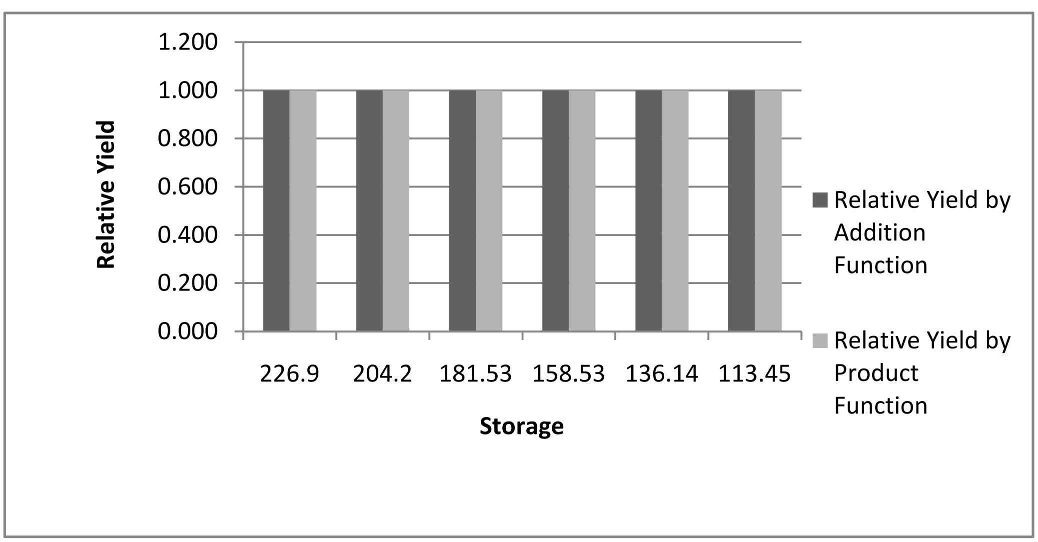


Figure 12: Relative Yield for Wheat at Different Storage Levels

DISCUSSION ON RESULTS

The results stated in the present chapter indicate that there is no deficit to any of the crops up to an initial storage of 136. 14 MCM. It was found that that deficit starts from an initial storage level of 113.45 MCM. The product type of objective function performs better than the addition type of the objective function in both the models.

CONCLUSION

Present study is conducted for reservoir operation for irrigation considering Samrat Ashok Sagar Reservoir Project as a case study using HSA technique. The optimization of the water stored in a reservoir is carried out to maximize the yield in a multi-crop scenario. The HSA model developed in the present study allocates the water optimally amongst various crops in different time periods. This also accounts for the deficits in the supply and the allocations of deficits to maximize the possible relative yields.It is observed that the model works well and generates a set of releases to meet the demand of different crops in various fortnights. Two models are developed and applied. The additive model adds squared deviations between the demands and the releases in all the periods for all the crops. The multiplicative model multiplies the squared deviation of each crop over all its periods and the product for all the crops is added. This model performs better than the additive model as regards the final yield of the individual crops is concerned. The multiplicative model is more realistic as regards the actual yield is concerned. The study indicates that the model presented can be used to determine the optimal reservoir operation for irrigation. The deficient storage conditions in the beginning of the Rabi season have a negative impact on the water supplies and the crops suffer deficits. However the results of the present study indicates that the deficits are minimized in case of deficient storage.

REFERENCES

1. Atrabi,Hamid Bashiri; Qaderi, Kourosh; Rheinheimer, David E. and Sharifi, Erfaneh (2015). "Application of Harmony Search Algorithm to Reservoir Operation Optimization" Water Resour Manage , Published Online September2015, DOI 10.1007/s11269-015-1143-3.
2. Bandaru, Sunith and Deb, Kalyanmoy; "Metaheuristic Techniques (2016). A School of Engineering Science, University of Sk¨ovde, Sk¨ovde 541 28, Sweden, Department of Electrical and Computer Engineering, Michigan State University, East Lansing, 428 S. Shaw Lane, 2120 EB, MI 48824, USA COIN Report Number 2016029, Published in Decision Sciences: Theory and Practice, Edited by Sengupta Raghu Nandan, Gupta Aparna and Dutta Joydeep, CRC Press, Taylor & Francis Group Published October 26,2016,pp. 693–750.
3. CWC (2014). Guidelines for Improving Water Use Efficiency in Irrigation, Domestic & Industrial Sectors" Performance Overview and Management Improvement Organization Irrigation Performance Overview Directorate, Central Water Commission, New Delhi, November, (2014), pp 1.
4. Food and Agriculture Organization, FAO (1998). Crop evapo-transpiration: Guidelines for computing crop requirements." http:// www.fao.org/docrep/X0490E/X0490E00.htm
5. Geem ,Zong Woo; Joong, Hoon Kim and Loganathan, G. V. (2001). A New Heuristic Optimization Algorithm: Harmony Search", SIMULATION 76:2, pp. 60-68.
6. Geem, Zong Woo (2007). Optimal Scheduling of Multiple Dam System Using Harmony Search Algorithm ", International Work-Conference on Artificial Neural Networks. IWANN 2007: Computational and Ambient Intelligence pp 316-323.
7. Kougias, Ioannis P. and Theodossiou, Nicolaos P. (2013). Application of the Harmony Search optimization algorithm for the solution of the multiple dam system scheduling" .Published online: 4 January 2012 © Springer Science, Business Media, LLC.
8. Planning Commission Government of India (2009). Report of the Task Force on Irrigation, May (2009), pp 6. https://pdfs.semanticscholar.org/c28f/cda2bccc75b10e1d540031269e82a5d9c9b0.pdf
9. World Resource Institute (2015). https://www.wri.org/blog/2015/02/3-maps-explain-india-s-growing-water-risks
10. Yang, X.S., (2009). Harmony Search as a Metaheuristic Algorithm, In: Music-Inspired Harmony Search Algorithm: Theory and Applications (Editor Z. W. Geem), Studies in Computational Intelligence, Springer Berlin, vol. 191, pp. 1-14.
11. Yoo, Do Guen and Hoon,Kim Joong, (2014). Meta-heuristic algorithms as tools for hydrological science",Geoscience Letters,Official Journal of the Asia Oceania Geosciences Society (AOGS), published 6 march ,2014 in Springeropen.