International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878, Volume-8 Issue-5, January 2020

# Optimization of Reservoir Operation using Linear Programming

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***Abstract*: The paper aims to derive the optimal releases monthly through linear programming for a single purpose reservoir. The releases from the reservoir are usually based upon the rule curves or operating policy adopted. The rule curve is the storage, indicating the water levels to be maintained in-order to satisfy the demand during the operation period. Linear programming (LP) is one of the global optimization techniques that have gained popularity as a means to attain reservoir operation. In the present study Linear Programming was used to develop an operation policy for Hemavathy Reservoir, Hassan District Karnataka, India. The decision variables were monthly reservoir releases for irrigation and initial storages in reservoir at beginning of the month. The constraint bound for the reservoir releases was reservoir storage capacity. The results derived by using Linear Programming shows that the downstream irrigation demands were satisfied and also considerable amount of water was conserved from reduced spills.***

***Index Terms*: Reservoir Operation, Linear Programming, Optimization, Rule curve.***

## I. INTRODUCTION

Water is a fundamental source for all forms of life and is essential for agriculture and industry purposes. In particular the industries like hydropower, irrigation and manufacturing sectors cover majority of the demands. The mains supply of water is through surface and ground water incurred by limited availability. All the urban and rural areas depend on nearby water storage bodies such as river, lake or reservoir. The reservoirs are artificial lake that are used to store or reserve the water for all its requirements (irrigation, power production, drinking purpose, flood control, recreation purpose etc) [1][2]. The limited access to water resources and increase in human need for water, calls for a strategic water management policy. The water distribution for drinking, agriculture and industry has been the main function for operation of reservoirs. The gross domestic product of many countries depends on agricultural products, corresponding to majority of water demand than other purposes. So, optimum operation and efficient management of water resources, along with it response to the demand leads to reduction in wastage of water and increasing the agricultural yield; and gaining sustainability. Optimization of reservoir operation has been a major area of study in water resources systems. For optimum reservoir operations, a set of rules need to be determined and the water storage volume for releases under various conditions should be formulated. Optimization models are useful tools to identify and suggest operating rules for reservoirs, but some computational presumptions restrict their efficacy and flexibility. The reservoir operation includes the flood operation that instructs initial release to provide room for adequate storage incoming as inflow and reducing the spills [9]. If the spill and release are in excess then flow rate should be monitored by routing. The operation of reservoir in non-monsoon months is more critical, so water should be distributed equitably. The rule curves decide the storages in practical and their maintenance is trivial. The lower rule curve or dead storage level is maintained to reserve the water for aquatic bodies. The advancement in reservoir operation for climate change impacts is essential. The revision of currently existing real-time operation for all the purposes is necessary. The study proposes original methodology for the reservoir operation to enhance the competence and consistency of the reservoir operation to adapt the climate changes by applying linear programming model as optimization tool. The consideration of uncertainty into the analysis of the work may improve the reservoir storage condition either by increase or decrease in water volume.

Manuscript published on January 30, 2020.
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## II. RESERVOIR OPERATION

The storage of a reservoir above dead storage is active storage. The surplus water released after satisfying the demand and full reservoir capacity are spills. The reservoirs are operated based on the rule curves; they are the levels in the reservoir that are maintained during operation [1][2]. During operation of reservoir the demands may be satisfied completely or partially. Thus the mode of releases that are controlled needs well defined operating rule. The simplest operation rule practiced commonly is standard operation policy. If there is insufficient water in the reservoir to meet the required demand, the reserves are emptied first to satisfy it. If the volume of water in the reservoir decreases, then the hedging policy will be introduced and curtailments are made, such that demand and releases are reduced.

A reservoir operating policy decides a sequence of release decisions for daily or monthly operational periods as specified. The state of the system of a reservoir in a period is the storage levels at the starting of a simulation along with the inflow to it [3]. When the operating policy is introduced then the reservoir operation are simulated for the different periods with a given sequence of inflows. Many optimization algorithms have been developed and also adopted for deriving reservoir operating policies. Still, the common operation policy practiced is standard operating policy, which is discussed in this section. Along with its importance, the optimization study has also been brought out. The standard operating policy (SOP) aims to meet the demand at full extent in each period based on the water availability. The supply demand policy seeks in releasing the water by prioritizing to reduce deficits based on the storage. This policy is significant in reducing the vulnerabilities.

## III. OPTIMIZATION

The optimization process enables clear understanding of the objective and its importance. The primitive solutions to achieve objectives are defined considering all aspects of the problem [5]. The tradeoffs between the objectives are of paramount importance. The problem definition phase provides a precise and clear statement of it. Then the observations made helps in identification and reasonable way to solve the issue. The problem defined continues in development of a mathematical model, which considers the reservoir system to execute all the aspects of the problem in resolving form.

Performing the sensitivity analysis allows us to determine the influential decision variables on the solution. It also determines the bias of each input data on the decision variables. Amount of default modification in measuring is determining the power of the model. Some of the popular methods adopted are linear, non-linear and dynamic programming.

Linear programming is the most significant optimization technique. It is an operation technique accepted globally and has been extensively used in water resource planning and management problems [3]. It is widely used for all variety of reservoir operations and it provides efficient solution through the algorithms; and also through many computer software packages that are available [4]. Many of the optimization software are available for commercial purposes to solve linear and non linear equations bounded by constraints.

Optimization problems that involve nonlinearities are called nonlinear programming (NLP) problems. Solutions to these programs are found using search procedures and finding the solutions are more tedious to determine, compared to linear programs. The major problem is difficulty in distinguishing between a local and global minima or maxima. Dynamic programming is a means of approach to a problem, problem involving a sequential decision making processes can be solved by the application of dynamic programming. The conditions for overall best results are investigated and achieved.

The simulation of reservoir operation is a search technique carried by trial and error approach. Many situations require planning and designing of water resource system and it may involve rigorous mathematical models that are resolved by simulation. The simulation also incorporates sensitive correlation among the variables, and describes the outcome or response of the operating system for a given set of inputs and operating conditions. Along with these many evolutionary algorithms are also used in optimization (artificial neural network, genetic algorithm, fuzzy logic etc)

Artificial neural network (ANN) is a numerical computing system made up of a number of interconnected processing elements called neurons, which process information through transformation functions. They are replicated from human nervous system. Genetic algorithm (GA) is inspired from animal generation system (reproduction, cross over, mutation etc) [4]. They are used to find the optimal solution to a given computational problem either maximizing or minimizing a particular function. They represent all evolutionary algorithms and its computation. GA imitates the biological processes of natural selection to resolve and find the optimum solution. These algorithms are more efficient in optimization compare to random search and exhaustive search techniques; and require minimum data set. This feature allows them to replicate the solutions to the problems than other methods (Fig. 1).

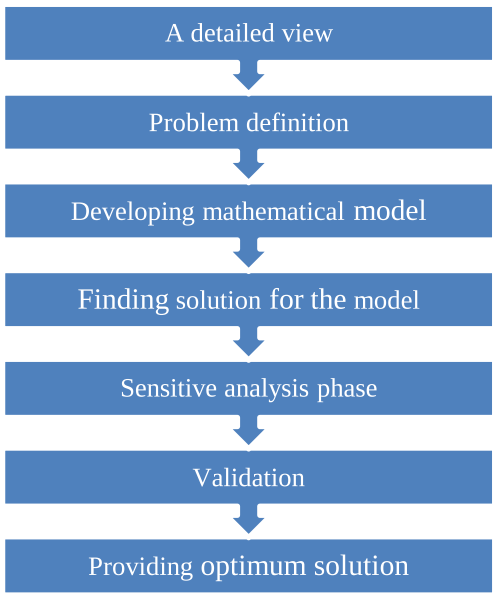


**Fig. 1.Schematic representation of optimization process**

Fuzzy logic systems are mainly used for controlling, system identification and also the pattern recognition problems. The reservoir performances are described by the performance indicators (Probability of failure, Volume reliability and Shortage Index)

## IV. STUDY AREA

The Hemavathy reservoir selected as study area (Fig. 2) is located in the south-western portion of Karnataka state Hassan, India. It has boundary with Chikkamagalur, Tumkur, Mandya, Mysore, Kodagu and Dakshina Kannada district [7]. The district spreads across a geographical area of 6814 sq.km and it lies between of $12^{0}$ 31’ N and $13^{0}$ 33’ N latitude and of $75^{0}$ 33’ E and $76^{0}$ 38’ E longitude.

Retrieval Number: E6174018520/2020©BEIESP
DOI:10.35940/ijrte.E6174.018520
Journal Website: www.ijrte.org

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

The length of the district from North to South is about 129 km and its breadth from east to west is about 116 km. Hassan district consists of 8 taluks and lies partly in the southern Malnad region. It also contains a transaction zone termed as semi Malnad region. The Southern area is bounded by 650m contour and is having the higher degree of slope. As per the 2011 census, the Hassan district population was 17,21,669. Out of which 14,16,996 is the rural population (82.31 %) and 3,04,673 (17.69 %) is urban population. In the past decade the urban growth of the city has been expanded rapidly by Hassan urban development authority.

### A. Input Data

The Hemavathy Reservoir flow details for a period of 2010 to 2013, was used to develop optimization model. The average data was considered in the study and the details are provided in the table below.

**Table- I: Hemavathy reservoir details for year 2010 in M[a]m$^3$**

| Months | Initial Storage | Inflow | Actual Release | Spill | Evaporation |
|---|---|---|---|---|---|
| Jan | 286.85 | 18.97 | 28.31 | 23.21 | 00.56 |
| Feb | 258.53 | 07.36 | 02.26 | 31.14 | 01.69 |
| Mar | 213.79 | 05.38 | 01.69 | 42.47 | 16.99 |
| Apr | 177.54 | 06.51 | 01.98 | 35.96 | 25.48 |
| May | 167.63 | 33.41 | 00 | 36.52 | 22.65 |
| Jun | 163.67 | 01.05 | 00 | 3.652 | 08.49 |
| Jul | 305.82 | 11.32 | 00 | 01.69 | 01.69 |
| Aug | 719.24 | 15.00 | 06.22 | 02.55 | 01.41 |
| Sep | 832.51 | 16.14 | 10.47 | 00.48 | 00.28 |
| Oct | 904.44 | 11.04 | 10.19 | 01.13 | 01.41 |
| Nov | 986.27 | 14.15 | 06.51 | 01.19 | 01.69 |
| Dec | 953.99 | 03.68 | 07.36 | 00.34 | 02.83 |

[a] Million

**Table- II: Hemavathy reservoir details for year 2011 in Mm$^3$**

| Months | Initial Storages | Inflow | Actual Release | Spill | Evaporation |
|---|---|---|---|---|---|
| Jan | 880.65 | 00.93 | 00.93 | 00.34 | 01.41 |
| Feb | 843.84 | 00.39 | 03.25 | 00.79 | 01.69 |
| Mar | 633.73 | 00.17 | 06.79 | 01.30 | 11.32 |
| Apr | 108.17 | 00.05 | 06.23 | 00.53 | 16.99 |
| May | 230.10 | 08.49 | 03.96 | 00.51 | 11.32 |
| Jun | 271.84 | 09.06 | 11.32 | 00.93 | 01.98 |
| Jul | 571.71 | 16.14 | 00 | 01.58 | 01.69 |
| Aug | 951.16 | 16.42 | 07.64 | 04.41 | 01.41 |
| Sep | 1002.41 | 17.27 | 09.91 | 06.85 | 01.13 |
| Oct | 898.77 | 07.93 | 10.76 | 01.01 | 01.41 |
| Nov | 791.45 | 06.79 | 11.32 | 00.96 | 01.13 |
| Dec | 527.82 | 01.58 | 10.47 | 00.96 | 01.41 |

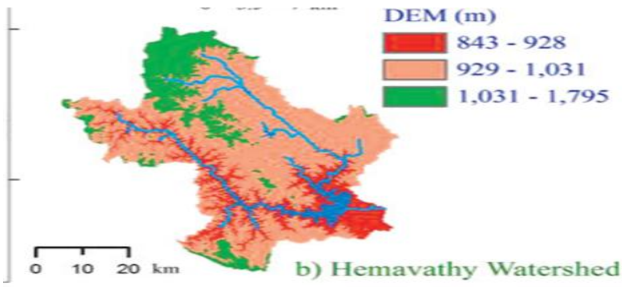


**Fig. 2.Hemavathy Watershed**

**Table- III: Hemavathy reservoir details for year 2012 in Mm$^3$**

| Months | Initial Storages | Inflow | Actual Release | Spill | Evaporation |
|---|---|---|---|---|---|
| Jan | 246.35 | 00.11 | 05.09 | 0.28 | 1.41 |
| Feb | 192.55 | 00.25 | 00.19 | 0.34 | 1.69 |
| Mar | 181.22 | 00.05 | 00 | 0.25 | 11.32 |
| Apr | 172.73 | 00.48 | 00 | 0.22 | 16.99 |
| May | 180.94 | 00.28 | 00 | 0.22 | 11.32 |
| Jun | 181.22 | 00.96 | 00 | 0.22 | 1.98 |
| Jul | 319.98 | 08.55 | 00 | 0.16 | 1.69 |
| Aug | 733.40 | 19.82 | 08.09 | 1.69 | 1.41 |
| Sep | 878.95 | 12.60 | 09.40 | 2.83 | 1.13 |
| Oct | 659.78 | 03.68 | 09.14 | 2.54 | 1.41 |
| Nov | 444.57 | 01.55 | 05.66 | 1.13 | 1.13 |
| Dec | 267.87 | 00.42 | 03.96 | 1.13 | 1.41 |

**Table- IV: Hemavathy reservoir details for year 2013 in Mm$^3$**

| Months | Initial Storages | Inflow | Actual Release | Spill | Evaporation |
|---|---|---|---|---|---|
| Jan | 206.14 | 0.11 | 0.28 | 0.28 | 0.56 |
| Feb | 176.13 | 0.08 | 0 | 1.13 | 1.69 |
| Mar | 201.61 | 0.05 | 0 | 0.22 | 16.99 |
| Apr | 144.98 | 0.085 | 0 | 0.42 | 25.48 |
| May | 109.01 | 0.22 | 0 | 1.84 | 22.65 |
| Jun | 16.19 | 9.34 | 6.51 | 2.43 | 8.49 |
| Jul | 705.08 | 31.14 | 4.10 | 4.58 | 1.69 |
| Aug | 1040.64 | 28.31 | 10.19 | 22.65 | 1.41 |
| Sep | 1030.73 | 8.49 | 8.49 | 1.01 | 0.28 |
| Oct | 1002.41 | 5.66 | 9.91 | 0.42 | 1.41 |
| Nov | 974.09 | 8.49 | 9.06 | 0.37 | 1.69 |
| Dec | 942.95 | 6.51 | 9.91 | 0.42 | 2.83 |

## V. METHODOLOGY

Linear programming (LP) technique is applied to improve the reservoir performances. The main objective is achieved by reducing the spills and shortages. The conditions of this optimization are:

- The volume of water released from the reservoir must satisfy the demand for each irrigation area.

- The volume of water storage in reservoirs must be up to the reservoir capacity only.

The optimal solution of this problem is applied with LP model [5][6]. The objective of the study focuses on maximizing the release and reducing the vulnerabilities.

Maximize $\sum_t R_t$

The Storage continuity equation is:

$S_{t+1} = S_t + I_t - EV_t - R_t - Spill_t$  for $t = 1, 2, \ldots, 12$

Where,

$Spill_t = 0$ ;  if $S_t + I_t - EV_t - R_t \le K$

$Spill_t = K - [S_t + I_t - EV_t - R_t]$;

if $S_t + I_t - EV_t - R_t > K$

$S_t \le 35.76$ ; $S_t \ge 0$; $R_t \le D_t$ ; $R_t \ge 0$;  for $t = 1, 2, \ldots, 12$

Where,

$S_t$ is the water storage volume in the reservoir at time t,

$S_{t+1}$ is the storage at the end of a time.

$I_t$ is the water inflow volume of the reservoir during time t,

$R_t$ is the water released volume of the reservoir during time t.

$O_t$ is the out flow from reservoir

$Ev_t$ is the evaporation K is the capacity

In the present work CropWat 8.0 is adopted for estimating the water requirement for different crops. It is based on soil, climate and type of the crop [6]. It can also be used in development of irrigation schedules for supplying water for varying crop patterns [11].

The excel solver is used in determining the optimum solution through linear programming for the reservoir releases and are compared with actual releases.

## VI. RESULTS AND DISCUSSION

The irrigation demand for the crop is estimated through CropWat 8.0 is represented in Fig. 3. Here we considered 3 crops to calculate the demand of water required for the cultivation in the 62000 hectare agricultural field.

The total irrigation water requirements were calculated by the following equation

$W_{irr} = ET_{crop} + W_{lp} + W_{ps} + W_l - P_e$.

$$ETo = \frac{0.408\,\Delta(Rn - Gn) + \Upsilon\frac{900}{T + 27}\,u2(es - ea)}{\Delta + \Upsilon(1 + 0.34\,u2)}$$

$ET_{crop} = K_c \times ET_o$

$P_e = 0.6*P—10/3$ for P(month)<=70/3mm.

$P_e = 0.8*P—24/3$ for P(month)<=70/3mm.

Where, $W_{irr}$ is the irrigation water requirement; $ET_{crop}$ is the crop evapotranspiration; $W_{lp}$ is the water required for land preparation; $W_{ps}$ is the percolation and seepage losses of water from paddy field; $W_l$ is the water required to establish standing water layer; $P_e$ is the effective precipitation; mean temperature (T); wind speed (u2); vapour pressure saturation (es), actual (ea) and slope (Δ); soil heat flux density (G); psychrometric constant (γ) and radiation (Rn).

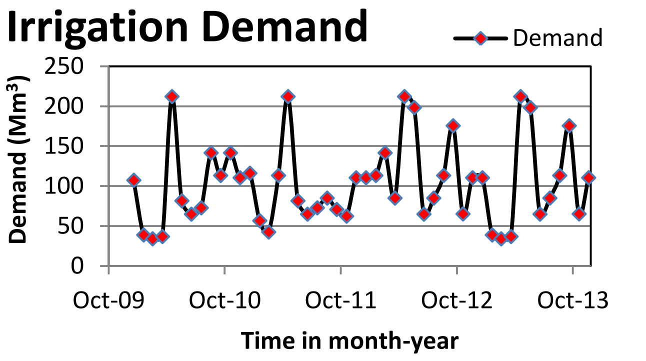


**Fig. 3.Crop water demand**

From Fig. 3, it was observed that the irrigation demand is more during the monsoon season and decreased during dry months.

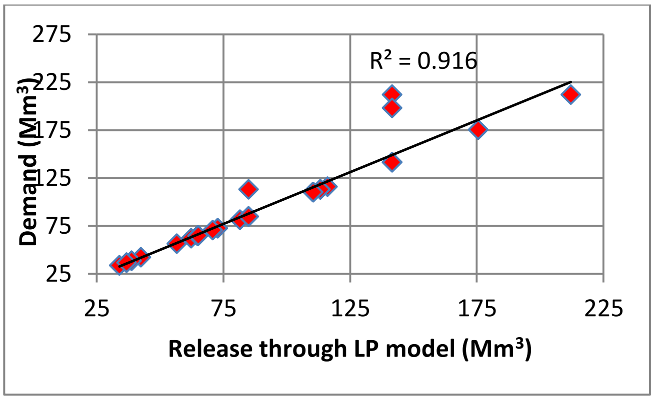


**Fig. 4.Regression of releases and demand**

The optimum water releases developed using LP model is compared with the actual releases (table 5). The model was successful in increasing the water release and water storage without any water shortages during monsoon and post monsoon [8][10]. From Regression plot (Fig. 4) it was observed that the LP model developed has satisfied very well as it was able to release the required demand. The results were tabulated by removing the outliers.

**Table 5 Comparison of the performances during operation of reservoir**

| Reservoir Performances | Actual Releases | LP Releases |
|---|---|---|
| **Volume Reliability** | 0.058 | 0.964 |
| **Shortage Ratio** | 0.942 | 0.036 |
| **Vulnerability ($Mm^3$)** | 212.09 | 70.50 |
| **Coefficient of Determination** | 0.0139 | 0.916 |

In addition, the analysis of results (table 5) shows that the actual releases currently adopted show severe shortage and the LP model developed outperform and reveals that the water has been released optimally from the reservoir. The release operations were consistent to the crop demand modeled, providing higher volume throughout cultivation and then gradually decreasing until harvesting.

## VII. CONCLUSION

The study proposes to minimize the irrigation demands for the Hemavathy reservoir. The results prove that the proposed methodology has successfully improved the efficiency of the reservoir. The operation decision assists the water release to meet the demand utmost without any shortage. The performances results show, that the optimization technique drastically improves the performance of the reservoir. The application of LP model is very appropriate for optimizing the operation system, since it employs the development of linear solutions based on the objectives and constraints. The solutions developed from the model allow the decision makers to consider the proposed optimal solutions.

## ACKNOWLEDGMENT

The authors wish to thank PWD, CWC, Irrigation department Karnataka for providing the data of the reservoir. The authors wish to thank the management Sapthagiri College of Engineering,

CIIRC, and JNNCE for supporting in carrying the research work. The authors also wish to thank the reviewers who helped to improve the frame work of the manuscript

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