Reservoir Operation Optimization for Dzuza Multipurpose Project in Nagaland Using Chance Constraint Linear Programming

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Abstract*: *In this paper a Chance Constraint Linear Programming (CCLP) was formulated for reservoir operation of Dzuza multipurpose project in Nagaland. The model can be used to determine the maximum annual hydropower that can be produced at different levels of reliability of meeting the irrigation demands. The irrigation requirement is taken as the priority which needs to be satisfied first. The release policy is defined by a chance constraint that the probability of meeting the irrigation release equaling or exceeding the irrigation demand, is not less than the specified value P. The CCLP model was run in LINGO 19.0 x 86 Version for various reliability levels of 60%, 65%, 70 % and 75% for meeting the irrigation demands with the objective of maximizing the annual hydropower generation. The model results gave global optimum solution for the down- stream release for the bed turbine, reservoir water elevation, hydropower produced by the bed turbine, end-of-period storage for each month and the monthly spill from the reservoir for all reliability levels and shows that as the reliability level of meeting the irrigation demand increases the annual hydropower generation decreases and as the reliability level of meeting the irrigation demand decreases, the annual hydropower production increases. For 75% reliability of meeting the irrigation demand, the maximum annual hydropower produced is 26.99969 M kWh. Beyond 75%, the solution was found to be infeasible. The optimal end-of-period storages (rule curve) for reservoir operation of Dzuza multipurpose project was also determined using the CCLP model. The graphs for Bed power release vs. Energy produced illustrated how hydropower produced increases with the quantity of bed power release.

***Keywords*:** *Chance constraint linear programming, hydropower, LINGO, optimization, Reservoir operation.*

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I. INTRODUCTION

Water resources system management evolves as policies, operating rules, environmental regulations, and climatic conditions change. Adaptive management is key for robust, reliable, and resilient water resources system management, including flood, water supply, ecosystem, and hydropower, and to use limited resources efficiently [2]. A reservoir operating policy is a sequence of release decisions in operational periods (such as months), specified as a function of the state. A rule curve indicates the desired reservoir release or storage volume at a given time of the year. Some rules identify storage volume targets that the operator is to maintain, as far as possible, and others identify storage zones, each associated with a particular release policy.

Optimization methods find a set of decision variables such that the objective function is optimized. The complexity of optimization problems depends upon the number of factors affecting a particular choice. Optimization techniques are meant to give global optimum solutions. Two classical approaches to deal with the hydrologic uncertainty in optimization models are the implicit stochastic optimization (ISO) and the explicit stochastic optimization (ESO). One of the most commonly used ESO techniques is Chance Constrained Linear Programming (CCLP) [9]. For models that include random variables, it may be appropriate in some situations to consider constraints that do not have to be satisfied all the time. Chance constraints specify the probability of a constraint being satisfied, or the fraction of the time a constraint has to apply [5]. The chance-constrained method is one of the major approaches to solving optimization problems under various uncertainties. It is a formulation of an optimization problem that ensures that the probability of meeting a certain constraint is above a certain level. In other words, it restricts the feasible region so that the confidence level of the solution is high. The chance-constrained method is a relatively robust approach; however, it is often difficult to solve [1]. The most common approach is to transform the chance constraints its deterministic functions and using cumulative distribution functions. In [7] the release policy is defined by a chance constraint that the probability of meeting the irrigation release equaling or exceeding the irrigation demand, is not less than the specified value P.

LINGO is a simple tool for utilizing the power of linear and nonlinear optimization to formulate large problems concisely, solve them, and analyze the solution [3]. Performance of LINGO and Discrete Differential Dynamic Programming (DDDP) based optimization models was evaluated by [6] on the basis of the objective function values achieved, the execution time required and the optimal state trajectories produced. Optimal storage trajectories obtained from both the models have been found. The LINGO model was found to be superior to DDDP model in terms of execution time, although optimal state trajectories produced by each model are identical.

II. OBJECTIVE

To formulate a Chance Constraint Linear Programming to determine i) the maximum annual hydropower produced from Dzuza multipurpose reservoir, while meeting the irrigation demands ii) the corresponding end-of-period storages (rule curve) for optimal reservoir operation of Dzuza multipurpose project and iii) To illustrate how the energy produced will vary with the bed power released for the specified level of reliability.

III. STUDY AREA

Dzuza Multipurpose Project is a hydropower generation and irrigation project and it is one of the conceptual Project of North Eastern Council for the people of Nagaland. The dam is proposed to be built across the river Dzuza (also known as Rengma- Zubza River). The dam site is located near Hazukhe Village in Dimapur district and it is at a distance of 30 km east from Dimapur city. Its Latitude is 25°54'34"N and Longitude is 93°58'47"E. The River Dzuza is a major tributary of the river Dhansiri and receives numerous small tributaries from the hill through which it makes its way. The catchment area of Dzuza River up to the proposed dam site is 344.01 sq. km and it covers Kohima and Dimapur district. The catchment is 'Dhansiri to Lohit confluence' and the watershed is Rengma watershed.

Figure 1: A Map showing the River Dzuza flowing in the Catchment area

IV. METHODOLOGY

A. Chance Constraint Linear Programming Formulation

The inflow to a reservoir is the most important random variable that introduces uncertainty in reservoir planning and operation problems. Due to the inability of the model to deal with two different random releases (into left and right bank canals) both of which have the same source of supply (reservoir) it is conceptualized that the reservoir releases water through a single irrigation canal.

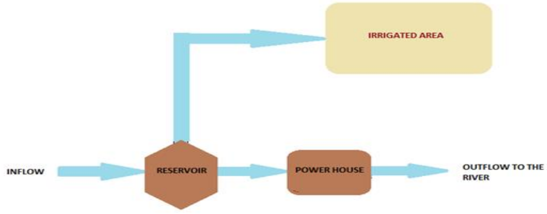

Figure 2: Flowchart of the multipurpose project

Since the project is primarily for irrigation, the irrigation demands are first met from the reservoir and the surplus storage is used to augment the power generation. The various steps for formulating the Chance Constraint Linear Programming are as follows:

Step 1: Release Policy

The reservoir release policy is defined by the chance constraint (1) which states that the probability of irrigation release in time 't' equaling or exceeding the irrigation demand is not less than a specified value P.

$$Pr\ [\ IRA_t \geq ID_t] \geq P \qquad (1)$$

Where, IRA_t- Irrigation release from the reservoir during time period t in MCM, ID_t- Irrigation demand for time period t in MCM (given), P- Specified reliability level for meeting the irrigation demands and t- Time period in months

Step 2: Reservoir Water Balance

The reservoir storage continuity relationship is expressed as:

$$S_t + I_t - IRA_t - BP_t - EV_t - OVF_t = S_{t+1} \qquad (2)$$

- Where, S_t – Storage in the reservoir at the beginning of time period t in MCM, I_t - Random inflow in to the reservoir in MCM for time period t, BP_t - Downstream release for bed power production in MCM for time period t, EV_t - Evaporation loss at the reservoir in MCM for time period t, S_{t+1} - Storage in the reservoir in MCM at the end of time period t and OVF_t- Overflow from the reservoir for time period t in MCM.
- Rearranging (2), we get

$$IRA_t = S_t - S_{t+1} + I_t - BP_t - EV_t - OVF_t \qquad (3)$$

Substituting (3) into the chance constraint (1), we get

$$Pr\ [S_{t+1} - S_t + BP_t + EV_t + ID_t + OVF_t \leq I_t] \geq \qquad (4)$$

This is the final form of the chance constraint. The deterministic equivalent is written using a linear decision rule (LDR) as follows.

Step 3: Linear Decision Rule

The linear decision rule (LDR) relates the irrigation release 'IRA_t', from the reservoir as a linear function of the water available in period t. The following LDR is considered:

$$IRA_t = S_t + I_t - BP_t - EV_t - OVF_t - b_t \qquad (5)$$

Where, b_t - non-random and non-negative operating policy parameter. Equation (5) indicates a release equal to the total available quantity, $S_t + I_t - BP_t - EV_t - OVF_t$, less some fixed amount b_t. In essence , the role of linear decision rule is to treat S_t as a deterministic formulation. Substituting (5) into the reservoir storage continuity equation (2), the linear storage rule is obtained.

$$S_{t+1}=b_t \quad (6a)$$

$$S_t=b_{t-1} \quad (6b)$$

Applying this rule in (5) it can be seen that the variance of inflow is directly transferred to the irrigation release, as such that EV_t , BP_t and OVF_t becomes functions of storage, all of which are now deterministic.

Step 4: Deterministic Equivalent

Substituting (6a) and (6b) in the chance constraint equation (4), the deterministic equivalent is written as:

$$b_t - b_{t-1} + BP_t + EV_t + ID_t + OVF_t \leq I_t^{(1-P)} \quad (7)$$

Where, $I_t^{(1-P)}$ denotes the CDF of reservoir inflow during the period t with CDF (1-P) or exceedance probability P.

Step 5: Other Constraints

(a) Storage Capacity Constraint: The storage in any time period t shall not be less than the dead storage capacity (K_d) and shall not exceed the total capacity of the reservoir (KT).

$$b_{t-1} \geq K_d \quad (8)$$

$$b_{t-1} \leq KT \quad (9)$$

Where, K_d - dead storage of the reservoir and KT - Total storage of the reservoir. With $b_0=b_{12}$ for a steady state solution.

(b) Power Plant Capacity: The energy produced by the bed turbine in any time period t, EB_t shall not exceed that corresponding to the Plant capacity, BPC, thus

$$EB_t \leq BPC \quad (10)$$

Where, EB_t - Power produced in M kWh for different time period t and BPC - Plant capacity in M kWh per month

(c) Overflow Constraints: The overflow constraint is provided in the linear programming model; otherwise the model will result in spill even when the reservoir storage is less than its capacity. The overflow constraint is mathematically express as:

$$OVF_t = I_t^{(1-P)} + b_{t-1} - ID_t - EV_t - BP_t - KT \quad (11)$$

(d) Head Storage Relationship: For computing the head over the turbine, the reservoir elevation H_t, in any period t above the river bed is taken to be the average of the elevations at the beginning and end of the period. The following linear relationship is assumed within the range of storages defined by (8) and (9).

$$H_t = \gamma[(b_{t-1} + b_t)/2] + \delta \quad (12)$$

Where, γ is the slope of the linear portion of the elevation-storage curve and δ is the intercept.

(e) Linear approximation for Power Production Function: A linear approximation of the nonlinear power production term, $EB_t = c\{BP_t\ (H_t - BTAIL)\}$ is expressed, following Sreenivasan & Vedula (1995), as

$$EB_t = c*[BP_t\ (H^0_t - BTAIL) + BP^0_t(H_t - BTAIL) - BP_t^0(H_t^0 - BTAIL)] \quad (13)$$

Where, BP_t^0- approximate value for the bed power release, BP_t, in period t, H_t^0 - Approximate value for the reservoir elevation, Ht, in period t, BTAIL- Tail water elevation of the bed turbine, and c- Constant to convert the product of the rate of flow and the head over the turbine into hydropower produced from the turbine. This constraint will be active only when the reservoir elevation is within the operating range (Hmin < H_t < Hmax) for bed turbine operation, Hmin and Hmax being specified. EB_t is set to zero outside this range.

Step 6: Objective Function

The objective function of this model is to maximize the annual hydropower production by the bed turbine of the Dzuza Multipurpose Project which can be represented as:

$$Maximize \sum EB_t \quad (14)$$

The objective function (14), along with constraints from (7) to (13) constitutes the chance constraint linear programming formulation.

B. Data Analysis

The data of the reservoir system were analyzed and the different variables to be used in the Chance Constraint Linear Programming were determined so that it can be used for running the model in Lingo. From the analysis of the available data, Total Storage of the reservoir, KT= 41 MCM, Dead Storage of the reservoir, K_d= 16 MCM, The Full Reservoir level (F.R.L.) of the reservoir = 276 m, The Mid Drawdown level (M.D.D.L) of the reservoir = 260 m, Maximum net head for bed turbine operation = 67 m, Minimum net head for bed turbine operation=51m and the Tail rise level, (BTAIL)= 209m. Therefore, the operating range for the reservoir elevation for power production which is specified as Hmin ≤ Ht ≤ Hmax is: Hmin= 209+51 = 260 m and Hmax = 209+67 = 276 m.

The installed capacity of the plant is 2*3.5 MW and the value of c=0.002268.So, assuming a load factor of 0.60 for a standard month having 730 hours, the plant capacity (BPC) in million kilowatt per month is:

BPC= 7000 *730*0.60 = 3.066 M kwh/month

To find out the Cumulative Distribution Function (CDF) of inflow, fourteen (14) years historical inflow data of the river was used. Gumbel Distribution was used for the plotting the CDF chart of inflow for all the months. The CDF chart corresponding to average of 14 year data of particular months arranged in a hydrological year from July to June and the irrigation requirement is given in the Table 1. The CDF of inflow for different specified reliability P and the irrigation requirement curve from hydrological year July to June is shown in Figure 3.

Table 1: CDF values of inflow in Dzuza River at the Dam site for different specified reliability P and the Irrigation requirement

Month	**t**	**Irrigation Requirement (MCM)**	**Inflow sequence for P**			
			F^{1}(0.60)	**F^{1}(0.65)**	**F^{1}(0.70)**	**F^{1}(0.75)**
July	1	12.147	336.2621	349.6421874	364.3744863	381.1933009
Aug	2	13.443	379.105	393.2543743	409.1397754	427.1099914
Sept	3	10.293	207.8135	214.9598383	222.8656202	231.8716504
Oct	4	7.006	136.4619	142.410252	149.0029344	156.5053122
Nov	5	4.716	72.0615	76.24998747	80.91538822	86.23492162
Dec	6	3.580	21.6487	22.48906752	23.417064	24.5484394
Jan	7	3.033	13.5976	14.11942312	14.69721282	15.35508331
Feb	8	3.872	10.9645	11.42849315	11.94248062	12.52875
Mar	9	2.763	8.358	8.65210396	8.977933089	9.349044586
Apr	10	3.468	16.1961	17.045442713	17.9855194	19.05682282
May	11	4.054	36.2485	38.24062606	40.44890444	42.96195556
June	12	8.1777	177.2116	185.7464211	195.663993	205.8175929

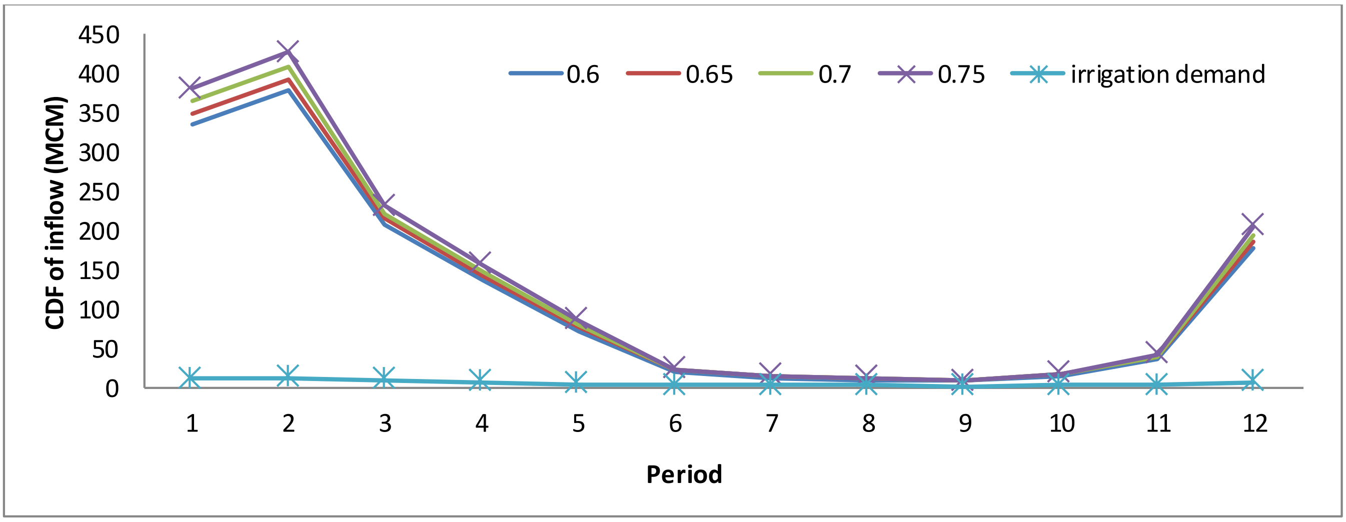

Fig 3: Irrigation requirement and the CDF of inflow for different specified Reliability

The storage elevation curve of the reservoir as shown in figure 4 was generated and it revealed that slope, $\gamma = 0.456$ and Intercept, $\delta = 257.11$

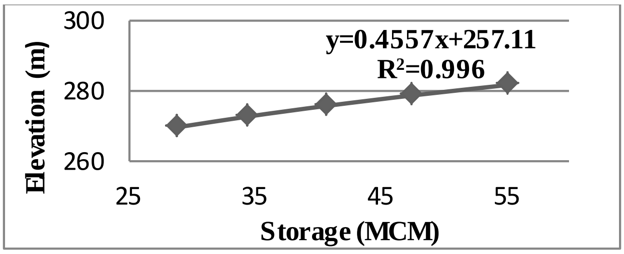

Figure 4: storage elevation curve of the Dzuza Multipurpose reservoir

C. Optimization in LINGO

The optimization can be performed once all of the data, except for the releases from reservoirs, have been given. The CCLP Model which has been formulated was run on LINGO Programming for different reliability levels of 60%, 65%, 70% and75% of meeting the irrigation demands. Each time a run is made for a particular value of P (specified reliability), the corresponding inflow sequence for 12 months has to be used and thus the Global optimum solution for the Chance Constraint Linear Programming for that specified reliability is found. The Optimization approach is shown in the Figure 5.

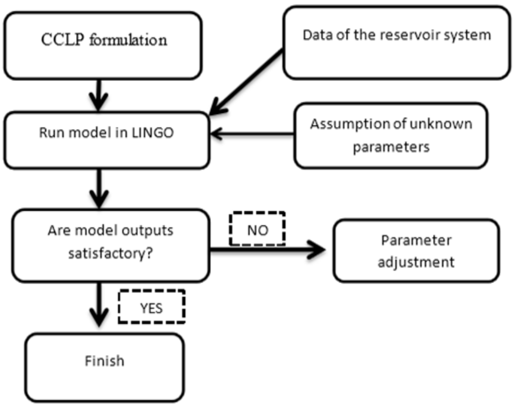

Figure 5: Optimization approach

For different reliability, a run is made where a reasonable value of H_t^0 and Bp_t^0 is assumed where H_t^0 is an approximate value of elevation of the reservoir for time period t and Bp_t^0 an approximate value of bed power release from the reservoir for time period t. If the values of H_t and BP_t in the solution are different than the values H_t^0 and Bp_t^0 that was assumed then a second run is made by replacing H_t^0 and BP_t^0 with the values of H_t and BP_t respectively which we obtained from the solution of the previous run and this procedure is continued until H_t converges with H_t^0 i.e., $H_t \approx H_t^0$ and BP_t converges with BP_t^0 i.e., $BP_t \approx BP_t^0$. Thus the Global optimum solution for the Chance Constraint Linear Programming for that specified reliability is found. The run is made by increasing the reliability level until the solution becomes infeasible. The highest reliability level of meeting the irrigation demand and the corresponding bed turbine power production is determined.

While running the program, right after the compilation phase, LINGO invokes an appropriate internal solver to begin searching for the optimal solution to the model. When the solver starts, it displays a solver status window on the computer screen. Figure 6 shows the solver status window for the linear reservoir problem having 75 % reliability of meeting the irrigation demand. This window is useful for monitoring the progress of the solver and the dimensions of the model. The solver window shown in Figure 6 provides the model class which is LP in the present case. Also the state of the solution achieved. In the present case, a global optimal solution with an objective function value was achieved after 17 iterations. The variables box shows the total number of variables in the model. Since it is a linear problem, the status window shows that there are no nonlinear variables in the model. The constraints box shows the total constraints in the model and the non-zeros box shows the total nonzero coefficients in the model.

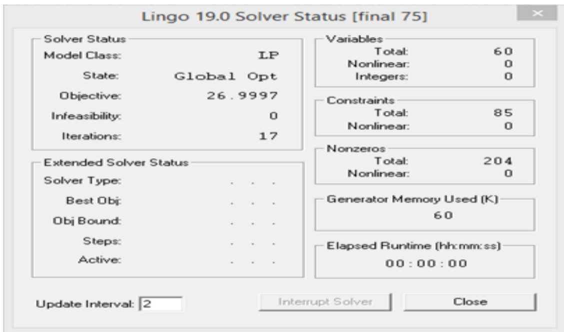

Figure 6: LINGO solver status window for 75 % reliability

V. RESULT AND DISCUSSION

Model runs were made for different reliability levels. For each run we got the maximum value of energy that can be generated in a year. Thus, the Global optimum solution for the Chance Constraint Linear Programming for that specified reliability is found. The maximum possible reliability for meeting the irrigation demand was found out to be 0.75 beyond which it became infeasible. Table 2 shows the maximized annual hydropower produced by the bed turbine for various reliability levels of meeting the irrigation demands. From the table it can be seen that as we increase the reliability of meeting the irrigation demands, the annual energy produced decreases.

Table 2: Reliability of meeting irrigation demand and the annual bed power production

Reliability	0.60	0.65	0.70	0.75
Annual Energy Produced (M kWh)	28.11805	27.74839	27.37785	26.99969

Figure 7 presents a plot of Reliability vs. Annual energy produced. From the curve we can find the maximum annual energy that can be produced by the bed turbine for a specified reliability level of meeting the irrigation demands; or alternatively, we may find the maximum reliability of irrigation associated with a given level of annual hydropower production.

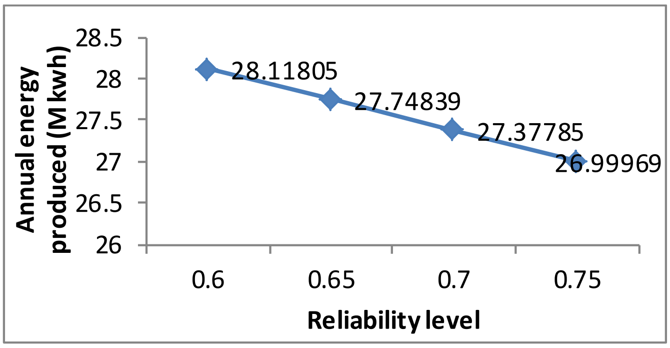

Figure 7: Annual energy produced Vs. Reliability

Comparing the model results of different reliability levels which has all generated global optimum solution, we can go with reliability level of 0.75 i.e. 75% reliability of meeting the irrigation demand since irrigation is the priority for this project and there is not much difference with the annual energy produced since the installed capacity of the power house is low.

Table 3 shows model results for reliability level 0.75 and it gives the down- stream release for the bed turbine, reservoir water elevation, hydropower produced by the bed turbine, end-of-period storage for each month and the monthly spill from the reservoir which is not used for generating electricity but is released to keep the downstream flow of the river.

Table 3: Model result for 75% reliability of meeting irrigation demand for Dzuza multipurpose project

75% reliability of meeting irrigation demand						
Period	**Month**	**Bed Power release (Mm^3)**	**Reservoir Elevation (m)**	**Energy produced (M kwh)**	**End-of-period storage (Mm^3)**	**overflow (Mm^3)**
t		**BP_t**	**h_t**	**EB_t**	**b_t**	**OVF_t**
1	July	24.39902	264.4060	3.066000	16	196.3915
2	Aug	24.39902	264.4060	3.066000	16	195.0955
3	Sept	24.39902	264.4060	3.066000	16	116.0783
4	Oct	23.98011	265.3739	3.066000	20.24511	45.41639
5	Nov	21.77811	271.0739	3.066000	40.99997	0
6	Dec	13.08737	275.8060	1.982946	41	0
7	Jan	7.408800	275.8060	1.122552	40.99997	0
8	Feb	4.212995	275.8060	0.7472640	41	0
9	Mar	3.587700	275.8060	0.5435940	40.99999	0
10	Apr	7.532793	275.8060	1.141339	41	0
11	May	20.3490	275.4565	3.066000	39.46719	0
12	June	22.25332	269.7565	3.066000	16	96.21697

The end-of-period storages define the rule curve for reservoir operation. Figure 8 represents the rule curve for optimal reservoir operation of the Dzuza Multipurpose project for 75 % reliability level. The figures 9 illustrate how water consumption will vary with power production for reliability level 0.75.

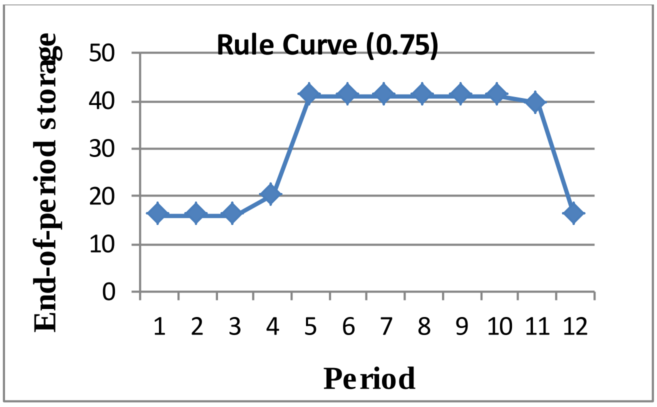

Figure 8: Rule curve of Dzuza Multipurpose project for 75% reliability

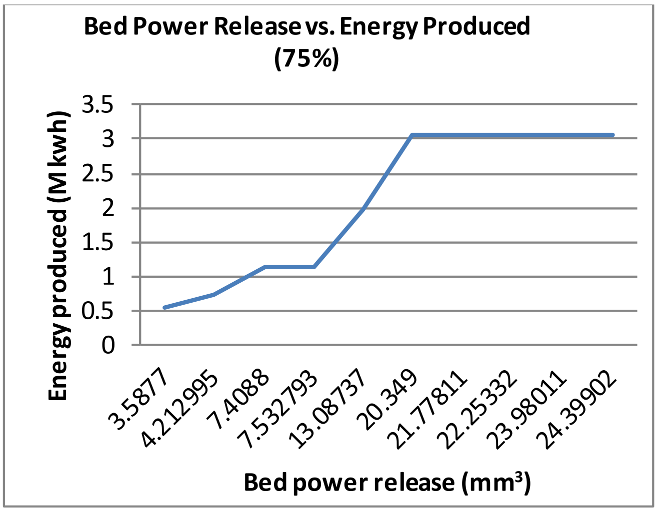

Figure 9: Bed power Release vs. Energy produced (75%)

VI. CONCLUSION

In this study, a Chance Constraint Linear Programming model was formulated and run in LINGO software for Dzuza Multipurpose project in Nagaland to determine the maximum annual hydropower production by the bed turbine while meeting the irrigation requirements for different reliability levels. The irrigation demand is kept as the priority which is to be satisfied first. The reservoir has two canal banks i.e. left bank and the right bank which irrigates water to the left bank and the right bank command areas but due to the model limitation of its inability to deal with two different random releases at a time, we have assumed that there is a single irrigation canal system. The model also considers a linear approximation for the non-linear power production function. The model was run in LINGO 19.0 x 86 Version for different specified value of P i.e. for 60%, 65%, 70% and 75%.

The model can be used to determine: I. The maximum annual hydropower that can be produced at different levels of reliability of meeting the irrigation demands for Dzuza multipurpose project, II. The maximum reliability of irrigation associated with a given level of hydropower production, III. The optimal end-of-period storages (rule curve) for reservoir operation of Dzuza multipurpose project and IV. The amount of energy produced with respect to the bed power release.

The model results gave the global optimum solution for down- stream release for the bed turbine, reservoir water elevation, hydropower produced by the bed turbine, end-of-period storage for each month and the monthly spill from the reservoir for all reliability levels. It was observed that as the reliability of meeting the irrigation demand increases, the annual hydropower production decreases. The maximum reliability of irrigation for the Dzuza multipurpose project was found to be 75% and the associated annual hydropower production is 26.99969 M kWh. . It was also observed that the maximum hydropower generated during the monsoon season is 3.0660 M kWh per month which is the maximum capacity of the Dzuza Multipurpose plant assuming a load factor of 0.60 for a standard month. The lowest hydropower generated for reliability 75% was observed in the month of March which was only 0.5435940 M kWh. The rule curve for optimal reservoir storage showed that for 75% reliability the reservoir storage should be kept in maximum level (i.e., Reservoir is kept in F.R.L.) during the non-rainy season from November to May to satisfy all the demands of irrigation and for hydropower generation since the inflow to the reservoir is low during these months. The reservoir level drops to the dead storage level in July but since inflow to the reservoir is sufficient, all the demands for irrigation and power generation are fully satisfied and this continues till October. The graphs for Bed power release vs. Energy produced illustrated how hydropower produced increases with the quantity of bed power release. It also indicates that the region is self-sufficient and in fact higher installed capacity can be provided.

For future Scopes, in terms of priority, if hydro power production is given more importance than irrigation then the results might change. Also the results will change if the installed capacity of the bed turbine is increased. The mathematical formulation can be run in other Software like MATLAB or Python and the results can be compared. A DDDP model can also be formulated for the same case study and the results can be compared with the results obtained from CCLP.

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