
Optimization Tool for Maximizing Hydropower Generation of Upper Kotmale Hydropower Plant "HydroPLUS"

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Abstract: An optimization tool as a form of decision support system is developed that addresses load allocation in a multi-unit hydroelectric plant. Although optimization in hydropower plants covers a broad range of areas such as individual unit level, plant level and system level, this paper covers specifically with such individual plant optimization. The tool named HydroPLUS, which is customized for Upper Kotmale Hydropower Plant, is an Excel spreadsheet application that provides operators a simple interface to use for loading hydro units utilizing inflow forecast as a main input to maximize generation. An overview of the Inflow Forecasting System using MIKE 11 Real-time software, being implemented in the plant, is provided together with its current status. It is provided an overview of MS Excel's Solver, a function of MS Excel, which is used by the tool. In the tool, some options are provided, namely, ability to specify the minimum and maximum water levels to be maintained in the reservoir during the optimization period, ability to specify if a unit is available for commitment and so on. Extensive simulation case studies using historical data indicate that there exists an opportunity for optimization of Upper Kotmale Hydropower Plant for generation using inflow forecast and usage of this tool will considerably enhance hydropower generation with gains of over 6.0% in plant performance.

Keywords: Upper Kotmale, Hydropower, Optimization, Inflow Forecasting, Excel Solver, MIKE11

1. Introduction

Upper Kotmale Power Station is a run-of-river hydropower plant with a daily regulating pond of 0.8 MCM effective capacity and has a catchment area of 317 km². The maximum water surface area is 0.25 km². Total installed capacity is 150MW with two Francis turbines. The plant on the average is expected to generate 409 GWh per annum.

Optimization of hydropower plants can be carried out at three levels namely, Individual unit level, Plant level and System level. Individual unit level optimization refers to running the hydropower unit at its best efficiency point which consumes less discharge thus saving water.

Managing the pond skilfully through the flexibility that operator gains with accurate inflow forecasts thus leading to enhancement of energy generation is an optimization at plant level. At system level, such as in a cascaded reservoir system involving multiple plants, it can be timing the available energy to meet peak demand or it can be hydro-thermal coordination as optimizing the system.

While this paper, in its present study, is focused on plant level optimization, it is worth noting that obtaining accurate inflow forecast and skilfully balancing this inflow forecast against available storage, reservoir capacity, turbine discharges and other constraints to maximize the plant generation are of paramount

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importance and are complex in nature.

At some instances, inflow to Upper Kotmale reservoir has risen up to 10 times in a matter of three to four hours to reach 350 m³/s the forecasted 05 year flood level.

The objective of this study is to provide a tool in the form of decision support system for Upper Kotmale Power Station that provides operators a simple interface to use for loading the units utilizing inflow forecast as a main input to maximize power generation and maintaining environmental release such as water release to the St Clair waterfall.

2. Optimization Process

A simple block diagram of the optimization process is presented in Figure 1. Forecasted inflow from MIKE 11 Real Time Software and Initial Water Level at the start of optimization period are input to the tool. Constraints such as Reservoir Capacity and Environmental release are programmed in the tool. It can also be specified Machine Availability, Minimum & Maximum water levels etc.

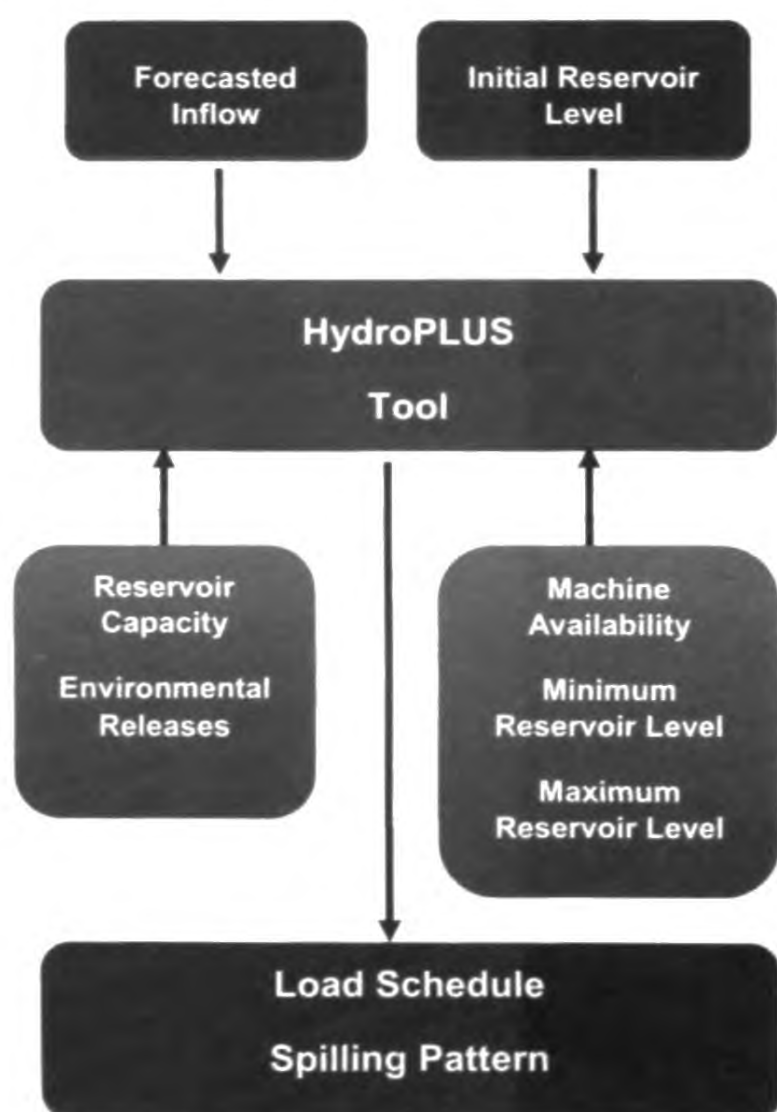


Figure 1 - Optimization Process

“HydroPLUS” is the name given to this optimization tool developed under this study. When run by the operator it presents optimized unit loading pattern for 24 hour period from the start time of optimization. The detail explanations of each block are given in the next sections.

3. Forecast of Reservoir Inflow

Accurate and reliable inflow forecasting forms an important basis for HydroPLUS tool to carry out the optimization effectively. MIKE 11 Real Time Software package from Danish Hydraulic Institute (DHI) is implemented in Upper Kotmale Power Station. It is worthy to note the difference between Flood Forecasting and Inflow Forecasting as both of them are often misunderstood. The flood is just a case of high inflow and for optimization of a reservoir is effectively addressed by not only forecasting flood but also inflow at all times. The flood forecasting is important to a reservoir such as that in Talawakelle as it borders a densely populated township for warning against very high flood levels that may be required for evacuation purposes and/or for warning downstream water users not to use the water in the river as there is a likelihood of opening the spillway gates.

There are five rainfall gauging and three water level gauging stations being established under Upper Kotmale Hydropower Project. The data is transmitted real time to Main Control Room in Power Station using a VHF network. This data is interfaced to MIKE 11 using MIKE Customized module. MIKE 11 Modelling system is built around a set of integrated modules for hydrology, hydrodynamics, flood forecasting etc. The following four main modules can be identified in MIKE 11 system.

- Rainfall-runoff module (RR)
- Hydrodynamic Module (HD)
- Flood Forecasting Module (FF)
- Data Assimilation Module (DA)

The main core module is Rainfall-Runoff module (RR) and is used to model each of the five sub basins of Upper Kotmale. This module is used to estimate the runoff volume generated from the rainfall to the basin or sub-catchment. Both current rainfall and rainfall forecast from reliable weather sources from internet as well as its own forecasting can be used in RR model. The Hydrodynamic module (HD) is used to perform the river routing. It calculates the flows and water levels within rivers. Flood forecasting module (FF) does the forecasting of inflow to the Talawakelle reservoir based on pre-calibrated RR and HD modules. Another module named Data Assimilation (DA) module acts as an updating module which reduces error of observed and forecasted inflow as the time evolves [1]. Once the total system is setup, inflow forecast is given at user specified intervals of 10 min, 30 min or 1 hour. At

present, installations of rainfall gauges and water level equipment are in progress. The calibration of RR and HD modules using historical rainfall & discharge data is completed by Lanka Hydraulic Institute (LHI) in Sri Lanka. However, calibration of FF module and set up of the MIKE Customized system are still on going and will be commissioned at site by the end of 2013 by DHI. Hence, verification of optimization of HydroPLUS was done using historical data as given in the case studies in later sections.

4. Problem Formulation

The constraints in the Upper Kotmale reservoir optimization at plant level, including conservation of mass, minimum storage and maximum storage, release to the St Clair waterfall, turbine discharge capacities, etc. are presented as follows.

4.1 Reservoir Water Balance Modelling

The equation of storage volume transformation is formulated according to the water balance: the storage at the end of one time step is equal to the initial storage at the beginning of next time step plus the incoming inflow volume during the time step minus the total released volume during the time step. It is expressed by the following equation (1).

$$S_{t+1} = S_t + (Q_t - R_t) \Delta t \dots\dots\dots (1)$$

$t = 1, 2, \dots, T$

Where,

- S_t Reservoir Storage at the beginning of time step t (m^3)
- Q_t Average forecasted inflow during time step t (m^3/s)
- R_t Average total discharge from the reservoir during time step t (m^3/s)
- Δt Time step duration (hr)
- T Total number of time steps in the optimization period

S_t is derived from the water level and the storage-level curve. Total discharge from the reservoir R_t in Upper Kotmale can be written as follows considering St Clair release, Turbine Discharge and spilling.

$$R_t = D_t + E_t + SP_t \dots\dots\dots (2)$$

Where,

- D_t Average total turbine discharge during time step t (m^3/s)
- E_t Average discharge to St Clair Waterfall during time step t (m^3/s)

- SP_t Average spilling through spillway gates during time step t (m^3/s)

Discharge to St Clair waterfall and is equal to a rate of $1.31 m^3/s$ from 0500hr to 1500hr every day which works out to $47250 m^3$ per day which is the statutory requirement of water release to ensure the visual beauty of the waterfall during the day time.[6]

4.2 Turbine Discharge Modelling

Total turbine discharge (D_t) is dependent on reservoir water level, tailrace level, Power output and Discharge (D) of a single turbine can be modelled as a cubic function of Power output as follows from the Turbine Model Test Data [3].

Let A_t be the difference between Reservoir water level and Tailrace level during time step t (m).

- A_t Difference between Reservoir Level and tailrace Level (m)
- P_t Power output (MW)
- C Number of synchronized units, $C = 1, 2$

IF ($A < 490$) AND ($C = 1$) THEN

$$D = \frac{[(490 - A) \times G11 + (A - 487) \times G12]}{3.0} \dots\dots\dots (3)$$

ELSEIF ($A \geq 490$) AND ($C = 1$) THEN

$$D = \frac{[(493.73 - A) \times G12 + (A - 490) \times G13]}{3.73} \dots\dots\dots (4)$$

ELSEIF ($A < 490$) AND ($C = 2$) THEN

$$D = \frac{[(490 - A) \times G21 + (A - 487) \times G22]}{3.0} \dots\dots\dots (5)$$

ELSEIF ($A \geq 490$) AND ($C = 2$) THEN

$$D = \frac{[(493.73 - A) \times G22 + (A - 490) \times G23]}{3.73} \dots\dots\dots (6)$$

Where,

$$G_{ij} = a_{ij} P^3 + b_{ij} P^2 + c_{ij} P + d_{ij} \dots\dots\dots (7)$$

$\forall i = 1, 2$ and $j = 1, 2, 3$

The a, b, c, d coefficients are as follows.

- $a_{11} = 0.00000719, \quad a_{12} = 0.00000699$
- $b_{11} = -0.00066977, \quad b_{12} = -0.00067913$
- $c_{11} = 0.22347804, \quad c_{12} = 0.22235891$
- $d_{11} = 1.48000195, \quad d_{12} = 1.48062322$
- $a_{13} = 0.00000675, \quad a_{21} = 0.00000996$
- $b_{13} = -0.00068570, \quad b_{21} = -0.00085761$
- $c_{13} = 0.22091472, \quad c_{21} = 0.22692553$
- $d_{13} = 1.48250266, \quad d_{21} = 1.47198975$
- $a_{22} = 0.00000960, \quad a_{23} = 0.00000919$

$$\begin{aligned}
 b_{22} &= -0.00083571, & b_{23} &= -0.00081176 \\
 c_{22} &= 0.22551339, & c_{23} &= 0.22394178 \\
 d_{22} &= 1.47409836, & d_{23} &= 1.47548317
 \end{aligned}$$

The above coefficients have been derived from the results of the turbine model test.

4.3 Reservoir Storage-Level Modelling

When the optimization is run, the tool does conversion from Water level to storage and vice versa. The storage level curve of Upper Kotmale is best fit to an octic equation from the civil data measurements [5].

$$S = aL_e^8 + bL_e^7 + cL_e^6 + dL_e^5 + eL_e^4 + fL_e^3 + gL_e^2 + hL_e \quad \dots\dots\dots(8)$$

Where,

- S Effective storage (m³), i.e Storage of the reservoir above minimum operating level of 1190.00
- L_e Effective Level difference, i.e. level above 1190.00 masl.

The coefficients of the equation are as follows.

$$\begin{aligned}
 a &= 3.213, & b &= -72.56, & c &= 650.4, \\
 d &= -2958, & e &= 7326, & f &= -9374 \\
 g &= 17760, & h &= 151500,
 \end{aligned}$$

4.4 The Objective Function

It can be identified three types of decision variables here. The decision variables, in this context, are those which measure the amounts of resources such as Unit output, to be allocated for maximizing the generation.

1. Average Power Output(P_t) during each hour for the 24 hours
2. Machine Running Status.(C_t) i.e. Whether at least one machine is

running or not.

3. Average Spilling Amount during each hour for the 24 hours (SP_t)

The objective of this exercise would be to maximize the water allocation to units as per the Power-Discharge relationship defined in Section 4.2, thus maximize generation. Constraints play a key role in determining what values can be assumed by decision variables, such as One unit output shall be less than 76MW and more than 30MW etc.

The objective function can be expressed as,

$$\text{Maximize } F(X) = \sum_{t=1}^T \left(\frac{P_t \times \Delta t}{1000} \right) \dots\dots\dots(9)$$

$T = 1, 2, \dots, T \quad T = 24$
 $\Delta t = 1 \text{ hr}$

Subjected to;

- C_t = 0 or 1
- if C_t = 1 and N = 1 ; 30 ≤ P_t ≤ 76
- if C_t = 1 and N = 2 ; 30 ≤ P_t ≤ 152
- if C_t = 0 ; P_t = 0
- L_{min} ≤ L_t ≤ L_{max}
- L_{min} ≥ 1190.00
- L_{max} ≤ 1194.00

Where,

- t Time Step in hrs; t = 1hr
- C_t Machine Running Status, 0 = Stop, 1 = At least one unit running
- N No of available units. N = 1 or 2
- P_t Average Power Output during time step t (MW)
- L_{min} User specified minimum level to be maintained in the reservoir during optimization (masl).
- L_{max} User specified maximum level, the reservoir is permitted to be filled during optimization (masl).

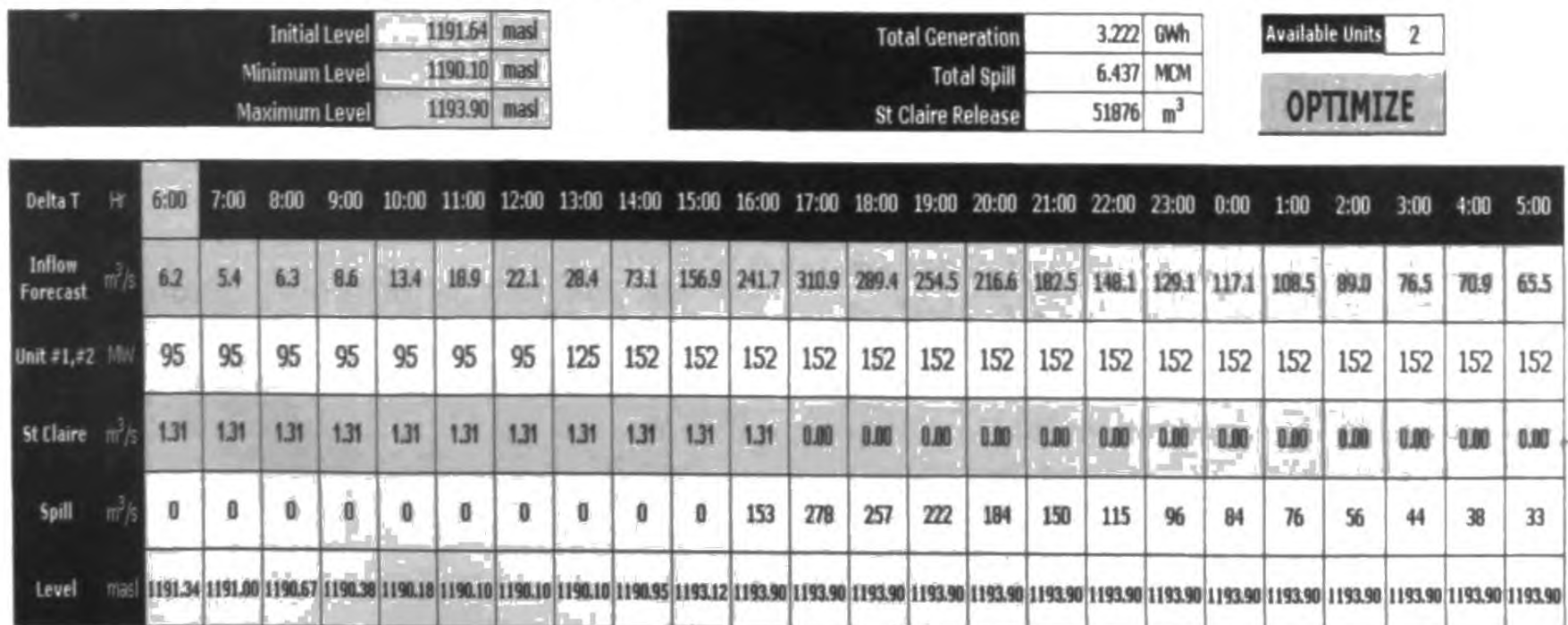


Figure 2 - HydroPLUS Tool Interface

Lt Reservoir Level at the beginning of time step t (masl)

5. HydroPLUS Optimization Tool

HydroPLUS is an MS Excel spreadsheet application developed in this study that provides operators a simple interface to use for loading of the units utilizing inflow forecast as a main input to maximize generation and maintaining environmental releases. In the tool, some options are provided, namely, ability to specify the minimum and maximum water levels to be maintained in the reservoir during the optimization period, ability to specify if a unit is available for commitment.

Excel's Solver is a function in MS Excel and may be used to solve linear and nonlinear optimization problems. Excel Standard Solver could be used to solve problems with up to 200 decision variables and 100 constraints. The user-programmable interface offered by the Excel Solver - a feature rarely found in other optimization modelling systems - is critically important to the many commercial users who are using Excel and Microsoft Office as a platform for developing custom applications. Every interactive, Graphical-User-Interface based action supported by the Excel Solver has a counterpart function call in Visual Basic for Applications (VBA), Excel's built-in programming language [2].

HydroPLUS optimization tool interface diagram is given in Figure 2 with actual historical data of inflow on May 13, 2013 in Upper Kotmale Power Station. The optimization problem defined in Section 4.0 was programmed in MS Excel using Solver and VBA to run the optimization automatically every time the button "OPTIMIZE" is clicked. Generalized Reduced Gradient (GRG) method [2] is used by the Solver when solving non-linear problems as in this case.

6. Case Study

Using one-hour interval inflow records of Upper Kotmale reservoir from May 2013 to Aug 2013, a simulation was carried out with the proposed HydroPLUS tool. Historical inflow records of a period of four months, starting from May 02, 2013, were selected for the case studies, as only during this period both units were available for generation and on the contrary, before May 2013 outages were taken from time to time for units due to testing. Further there were many instances during this period where sharp rise and recess of the inflow was found and it was a very suitable condition

to test the optimization tool to its maximum capability. The minimum and maximum inflow values recorded during this period were 5 m³/s and 350 m³/s respectively. They were observed on May 12 & 13, 2013 [6].

Hourly average inflow values in the selected period were utilized in the tool which was run for each hour. In the tool, the maximum and minimum reservoir levels were kept at 1193.90 and 1190.10 respectively throughout the selected time period.

The following are the steps performed in the tool to obtain the optimized generation for the selected period.

- Step 1 : Starting time was set as 06:00hrs on May 02, 2013. Other times were automatically populated.
- Step 2 : Hourly average inflows for the 24 hours starting from 06:00hrs, May 02, 2013 was input to the tool.
- Step 3 : Actual reservoir level at 06:00hrs on May 02, 2013 was input as the initial reservoir level.
- Step 4 : Average St. Clair release was input accordingly
- Step 5 : "Optimize" button was clicked.
- Step 6 : The following data were recorded from the optimized loading pattern given by the tool,
 - Generator load for the hour 06:00 - 07:00
 - Spill volume for the hour 06:00 - 07:00
 - Reservoir level at 07:00hrs
- Step 7 : Starting time was set as 07:00hrs for the next optimization
- Step 8 : Hourly average inflow for the 24 hours starting 07:00hrs, May 02, 2013 was input to the tool.
- Step 9 : St.Clair release was adjusted accordingly
- Step 10 : Reservoir level at 07:00hrs as given by the tool was input as the initial reservoir level.
- Step 11 : "Optimize" button was clicked.
- Step 12 : The process was repeated for each hour of each day for the selected period of four month.

At the end of this process, generator loads given by the tool for every hour was added up to get the optimized generation for the selected period.

6.1 Generation Optimization

The generation proposed by the tool was required to be compared with the actual generation in order to obtain the gain in optimization. However, it was observed from the actual plant despatch pattern, during certain times of the optimization period that units had been run at reduced loads instead of full load of 152MW while spilling due to system level requirements such as inability to de-load thermal machines or reduced system demand, etc. Therefore it is required to adjust the Actual Generation assuming machines were run at 152MW while spilling to negate the effect of this system level influence before being compared with the optimized generation in order to find the gain by the tool which, at present, is designed for plant level only.

The actual generation before adjustment, optimized generation and their difference are tabulated in Table 1.

Month	Actual Generation [GWh]	Optimized Generation [GWh]	Difference [GWh]
May	40.388	43.228	2.840
June	86.173	104.969	18.796
July	88.799	107.172	18.373
August	67.796	74.465	6.669
Total	283.156	329.834	46.678

Table 1 - Comparison of actual and optimized generations & their difference

As per the table 1, it can be seen that the difference in two generations values are somewhat high in June, July and August as attributable to earlier discussed system level effect.

From the plant data, the cases were identified where units were running at reduced loads while spilling and they were adjusted to full loads to obtain the adjusted actual generation as summarized in the Table 2 for each month.

Month	Actual Generation [GWh]	Adjustment [GWh]	Adjusted Actual Generation [GWh]
May	40.388	0.00	40.388
June	86.173	12.71	98.883
July	88.799	13.04	101.839
August	67.796	2.30	70.096
Total	283.156	28.05	311.206

Table 2 - Adjusted actual generation

Then, this adjusted actual generation was compared with the optimized generation of the tool. The gain and Percentage gain were also found and tabulated as in Table 3.

Month	Adjusted Actual Generation [GWh]	Optimized Generation [GWh]	Gain [GWh]	Percentage Gain [%]
May	40.388	43.228	2.840	7.03
June	98.883	104.696	6.086	6.15
July	101.839	107.172	5.333	5.24
August	70.096	74.465	4.369	6.23
Total	311.206	329.834	18.628	5.99

Table 3 - Comparison of Adjusted Actual Generation and Optimized Generation with Gain & Percentage Gain

It could be seen from Table 3 that a gain of about 6% could be achieved from this optimization by HydroPLUS.

Actual Generation, Adjusted Actual Generation and Optimized generation were plotted in Figure 3 for each month in this period.

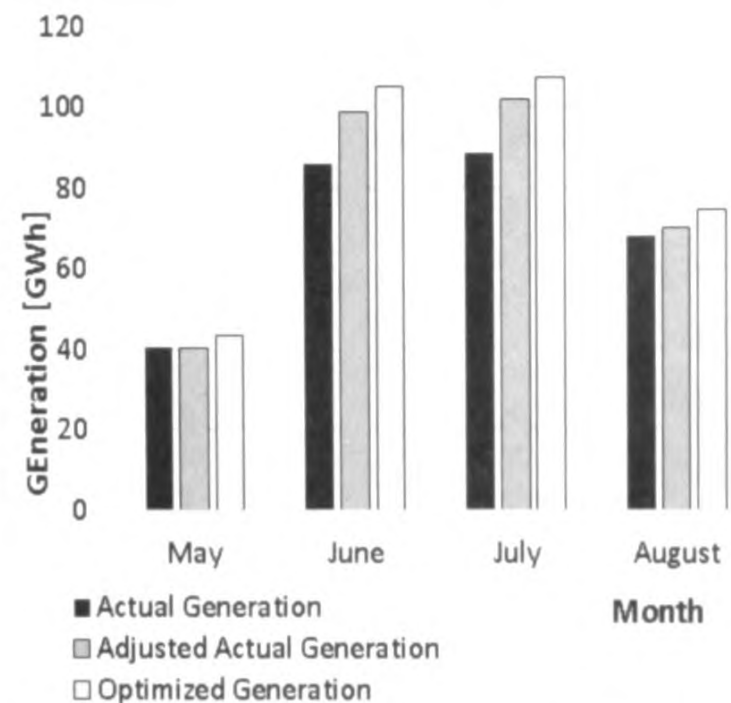


Figure 3 - Actual Generation, Adjusted Actual Generation and Optimized Generation for each month

The effect of the optimization by the tool for three different cases of inflow pattern was analysed as follows.

Case A : Sharp Rise of Inflow

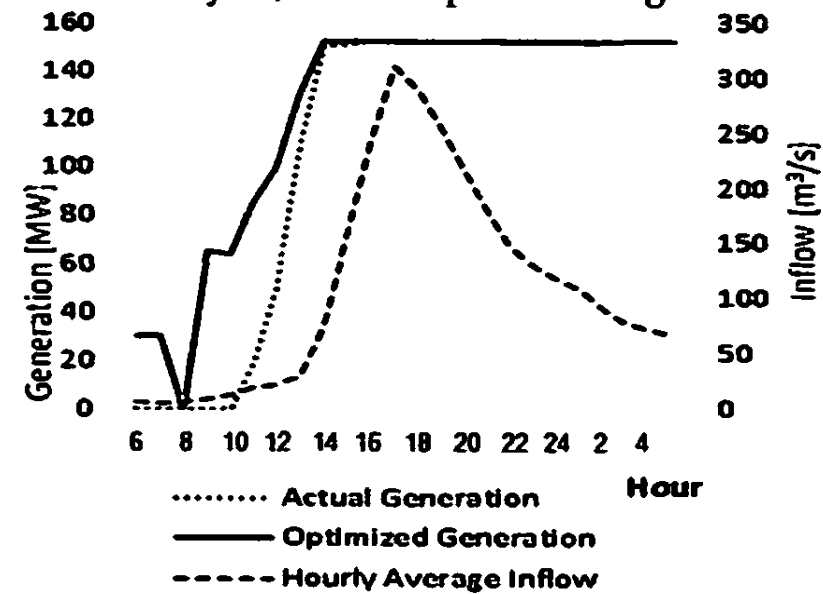
Case B : Sharp Reduction of Inflow

Case C : Low Inflow

For each of the above cases two graphs were plotted using data of optimized tool and actual data, i.e. Unit Power vs. time and Reservoir Level vs. time.

Case A: Sharp Rise of inflow experienced on May 13, 2013

Optimized Generation Load given by the tool, Actual Generation load and Inflow recorded during each hour for the 24 hour beginning at 0600 on May 13, 2013 are plotted in figure 4.



Generation	Actual	Optimized	Gain
GWh	2.560	2.937	0.377

Figure 4 - Comparison of actual and optimized generations with the average hourly inflow on May 13, 2013

Actual reservoir levels and levels that would reach when optimization tool is used for each hour are are plotted with inflow in Figure 5.

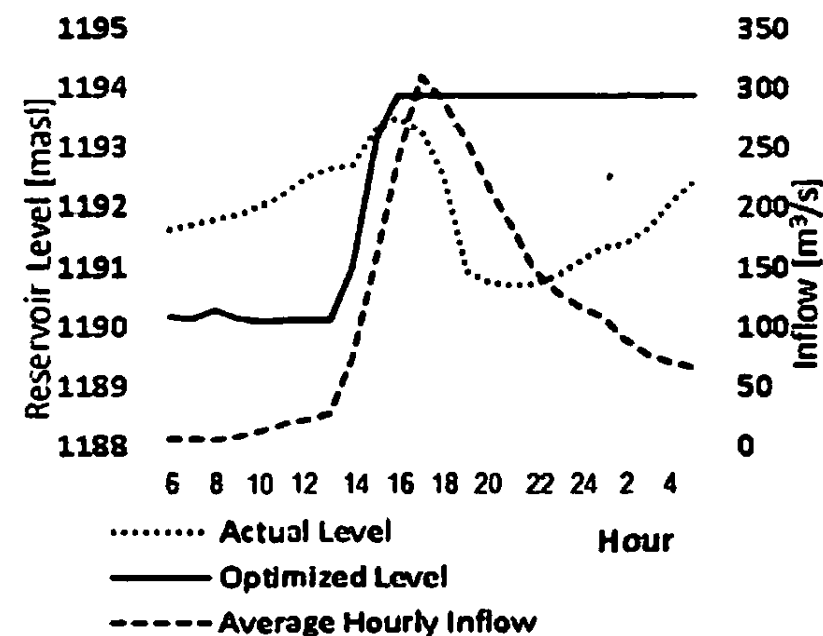
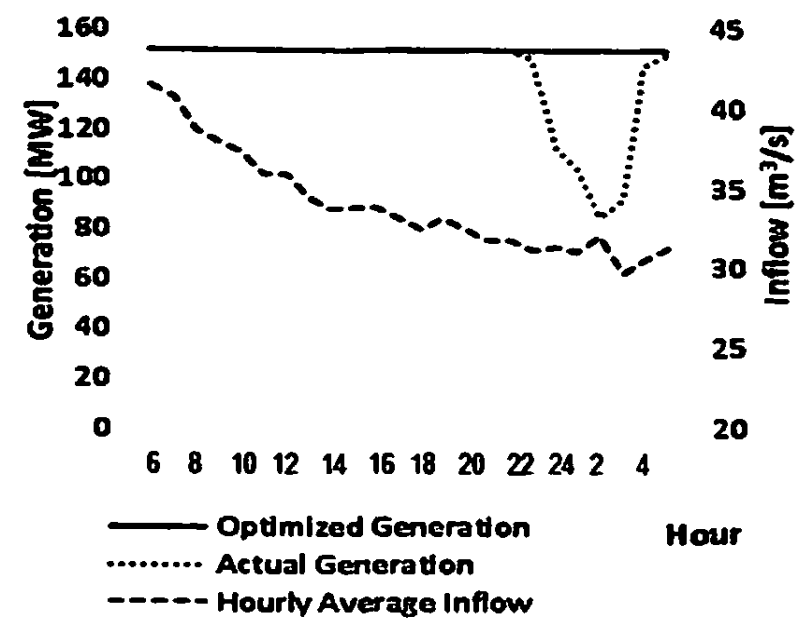


Figure 5 - Comparison of actual and optimized reservoir levels with the average hourly inflow for May 13, 2013

As per figure 4 and figure 5 it could be observed that as the inflow forecasts a sharp rise, the optimization tool, having been proactive, increases the generation well in advance and reduces the reservoir level to minimize any future spilling and to maximize the generation, in anticipation of the high inflow, thus managing the capacity of the reservoir effectively.

Case B: Sharp Reduction of inflow experienced on June 09, 2013



Generation	Actual	Optimized	Gain
GWh	3.390	3.648	0.258

Figure 6 - Comparison of actual and optimized generations with the average hourly inflow for June 09, 2013

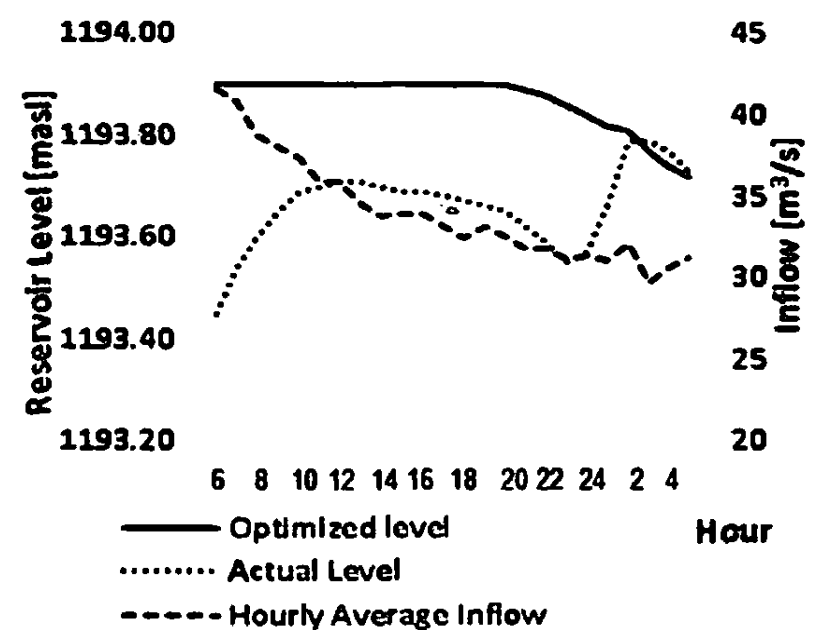
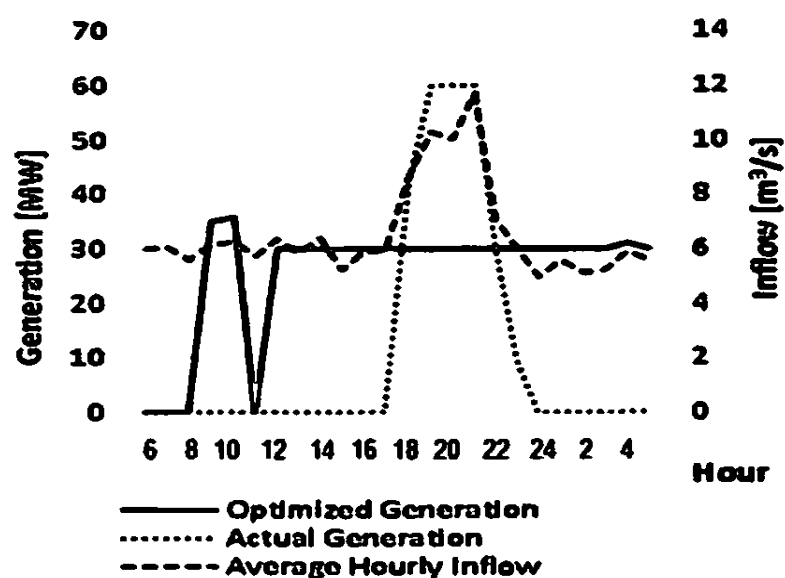


Figure 7 - Comparison of actual and optimized reservoir levels with the average hourly inflow for June 09, 2013

As per figure 6 and figure 7 it could be observed when the inflow is in the decline, the tool allows to fill the reservoir before it stops spilling, thus reducing the spilling volume and also allowing high generation even when the inflow is low. It should be clear from the above that the optimized decisions cannot be taken by human intervention only.

Case C: Low inflow experienced on May 12, 2013



Generation	Actual	Optimized	Gain
GWh	0.565	0.612	0.047

Figure 8 - Comparison of actual and optimized generations with the average hourly inflow for May 12, 2013

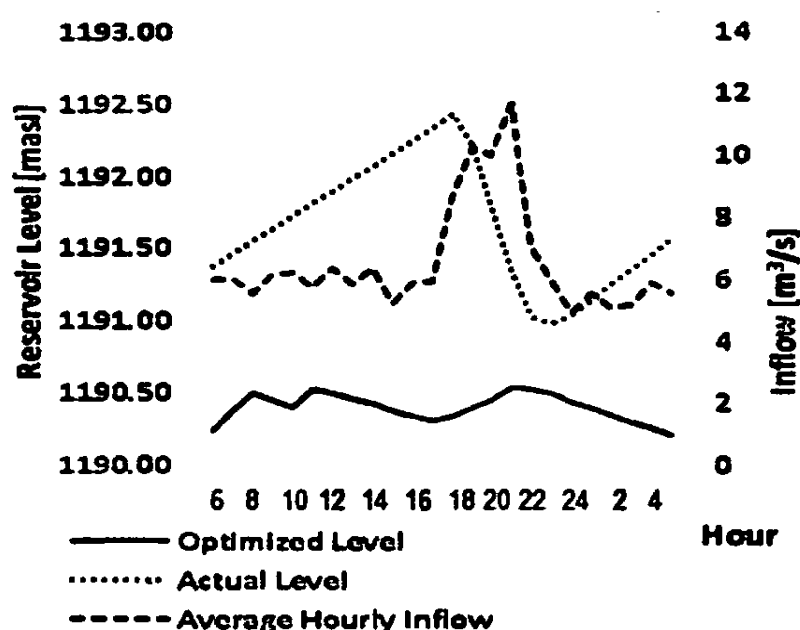


Figure 9 - Comparison of actual and optimized reservoir levels with the average hourly inflow for May 12, 2013

When the inflow is very low and neither rising nor reducing sharply, as in the case on May 12, 2013, could it be observed from figure 8 and figure 9, that there was no significant gain in optimization as in the Case A & B. Any clear pattern could not be recognized in either generation or reservoir level.

7. Conclusion

It is important to consider some plant level optimization when dispatching units in hydropower stations. HydroPLUS is a tool that can be conveniently customized to any hydropower station with a quest for energy optimization.

Case studies on Upper Kotmale Power Station reveal that there is an optimization in hydropower plant at plant level and it amounts to a gain of 6% in plant performance.

As future developments for this tool, it is possible to introduce some weightage on the time slots so that units are given highest priority during peak time. Further, at present, the tool does not have a sense of number of starts & stops, so it can be incorporated into the tool in future to reduce the number of starts & stops. Running the units at their Best Efficiency Points (BEP), in other words, unit level optimization can also be considered in the tool. Facility to specify non-availability of a unit during certain time slot could also be a future development.

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