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Full Length Research Paper

Modeling hydropower plant system to improve its reservoir operation

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One way of improving water management is increasing the efficiency of utilization of dam reservoirs. Even small improvement in reservoir operation can lead to large benefits. But there is no universal solution for reservoir operation problems. Hence, it is necessary to study the system and determine optimal reservoir operation guides for each scheme. In the present study, Melka Wakana Hydropower Plant in Ethiopia has been modeled and studied. The tool used was Powersim Simulation software. Mean monthly data of reservoir inflow, evaporation rate, recorded energy production; recorded discharge (turbine flow) and recorded reservoir elevation were used as time series input data. Different variables and relationships between variables were defined along with the constraints. After developing and calibrating the model successfully, detailed simulation analysis has been carried out by controlling reservoir releases for energy production, taking into consideration; increasing yearly energy production and improving the uniformity of monthly energy production. The results of the simulation analyses indicated that the yearly energy production was increased by 5.67% while evaporation loss was reduced by 38.33%. But this power plant still produces below its design capacity by 12.21%.The uniformity of monthly energy production from this plant was also improved. The new reservoir operation guide curve has been developed for the optimum energy production from this plant.

Key words: Guide curve, simulation model, reservoir operation, hydropower, energy production, water resources management.

INTRODUCTION

The Melka Wakana hydropower plant, which is located at the upper part of the Wabi Shebelle river basin of Ethiopia, is a single purpose scheme. The Wabi Shebelle basin stretches from Ethiopia High Plateaus to the Indian Ocean in Somalia. Within Ethiopia, it is located between 9°30'N and 5°N latitudes and 38°30'E and 45°E longitudes. This river basin has a potential of about 5400 GWH/year (Bosona, 2004; WWDSE, 2003) and Melka Wakana scheme is the only existing hydro power plant under operation in this river basin. This hydropower plant was commissioned in the year 1988 to produce 153 MW of electric power. The plant has four units of 38.25 MW each. The installed turbine type is Vertical Francis with rated speed of 600 rpm and turbine net head of 297 m. The plant was designed to produce annual firm energy of 434 GWh and annual average energy of 543 GWh (see Table 1).

Recently conducted studies (Awulachew et al., 2007) indicated that in the Wabi Shebele basin in Ethiopia, there are about 149 potential irrigation sites identified with estimated potential of 237,905 ha of irrigable area. Some of these sites are located in the catchments area of the Melka Wakena Reservoir. There are also about 6 proposed hydropower sites in the river basin (Bosona, 2004). The development of new water infrastructures in the basin and integrated management of water resources are required for sustainable socio-economic development of the area. Consequently, the operation of the existing single purpose reservoir of Melka Wakena will be

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Table 1. Main characteristics of installed turbine and generator.

Description	Characteristic values
Powerhouse location	On ground surface
Number of units	4 units(equal capacity)
Turbine type	Vertical Francis
Turbine rated speed	600 rpm
Net head of the turbine	297 m
Maximum turbine discharge	15 m^3/s
Generator type	3-phase synchronous
Generator related speed	600 rpm
Generator Installed capacity	153 MW
Annual firm energy production	434 GWH
Annual average energy production	543 GWH

influenced by the new water resources development to be introduced in the basin. The development of irrigation and hydropower projects in the upstream and down-stream of Melka Wakena Reservoir will initiate integrated water management which includes the principles of multi-purpose as well as multi-reservoir operation techniques. In that case, all possible benefits such as irrigation and fishing for food production (mainly), hydropower for national and local power supply, water for recreational facilities, flood protection and water for environmental flow should be taken into consideration.

Previous studies (Gourbesvive, 2008) indicate that in the next 30 years water use will increase by 50% in the world. By 2025 about 4 billion people will live under conditions of severe water stress. Continuous deterioration in water quality in most developing countries is additional challenge. Therefore, development of priority water infrastructures and improvements of water management have essential and complementary roles in contributing to sustainable growth and poverty reduction in developing countries like Ethiopia. One way of improving water management is through increasing the efficiency of utilization of dam reservoirs.

Although numerous simulation and optimization models have been developed over the past decade, the selection of an appropriate model for the derivation of reservoir operating guide curves is difficult and there is a scope for further improvement (Jothiprakash and Ganesan, 2006).

Reservoir operation is a complex task involving numerous hydrological, technical, economical, environmental, institutional and political considerations. There is no general algorithm that covers all type of reservoir operation problems. The choice for techniques usually depends on the reservoir specific system characteristics, data availability, the objectives specified and the constraints imposed (Bosona, 2004).

Different reservoir operation models have been developed and applied for planning studies to formulate and evaluate alternative plans for solving water management problems; for feasibility studies of proposed construction projects as well as for re-operation of existing reservoir systems. Acres Reservoir Simulation Package, ARSP (Daene, 2004) was developed by Acres International Corporation and is a general multi-purpose and multi-reservoir simulation program which determines the allocation of water through simulation according to user specified priorities. HEC-ResSim (Daene, 2004) is Reservoir System Simulation Model created by the U.S. Army Corp of Engineers and is used to simulate reservoir operations including all characteristics of a reservoir and channel routing downstream. Water Evaluation and Planning System, WEAP (Daene, 2004) is a model developed by the Stockholm Environment Institute's Boston Center. It is designed to assist water management decision makers in evaluating water policies and developing sustainable water resource management plans. Different dynamic simulation packages have been applied to water resources modeling. This includes the software STELLA, POWERSIM, VENSIM and GOLDSIM (Daene, 2004; Powersim Corporation, 1997).

In the contemporary reservoir operations, there is a challenge in closing the gap between theoretical reservoir operation and the real-world implementation (Mohamad et al., 2008). It is important to utilize the existing reservoirs efficiently by re- evaluating and improving the reservoir management. But there is no universal solution for reservoir operation problems. Therefore it is important to study the problems and determine optimal reservoir operation guides for each scheme. One of the reported problems of Melka Wakena Plant is that it is sometimes idle due to shortage of water in the reservoir. The reservoir has never touched its full reservoir level (FRL) since its commissioning except in the year 1998 when the spillway spilled for only two months in the rainy season (Bosona, 2004). This problem can be aggravated by the new development of irrigation projects in the catchments area of the reservoir which can reduce reservoir inflow. It should be investigated further to identify if this plant produces the amount of its design capacity or not. Therefore it is important to study this power plant system using powerful simulation tools. In this study Powersim Simulation Software has been used to model this Power Plant System and investigate the possible improvement in its reservoir operation.

The main objective of this study was to develop new reservoir operation guide curve for the Melka Wakena hydropower plant system to increase yearly energy production and to improve the uniformity of energy production throughout the year. It was also intended to quantify the gap between the actual production and design capacity and to investigate the possibility of saving water by reducing water losses. The saved water can be used by the rural communities in the catchments area, for irrigation, fishing and potable water supply for both human and animal husbandry which will contribute to the promotion of food security in the region.

METHODOLOGY

The tool used in this study was Powersim simulation software. It is windows-based software for creating system dynamics models. It is an object-oriented package that is used for hierarchical modeling with an unlimited depth of sub models. Its packages allow for the on-screen construction of a flow-chart style representation of a simulation model. It has a wide variety of objects for presentation of simulation results in graphs, simple numeric display, or tables. Powersim supports Dynamic Data Exchange (DDE) using standard Windows protocol and boasts an Application Programmers' Interface (API) which allows programmers to connect Powersim applications to programs developed in C++, Visual Basic, or Delphi (D. Chapman, UniServe Science, News Volume 8 November 1997).

Powersim can be used to model an imaginary or real system. It enables the user to create a visual image of the problem. By running the model the user can observe the effects of decisions over time, discover potential problem areas and make adjustments in a risk-free environment (Figure 1). It utilizes the system dynamics method to model the system and simulate its behavior over time. It offers the user a wide array of options to control the simulation's behavior. It has been successfully used to create simulations across a wide spectrum of industries and business such as strategic planning, resources management, crisis planning and management and process re-engineering (Daene, 2004; Powersim Corporation, 1997). However it has not been widely used for Reservoir Operation Modeling.

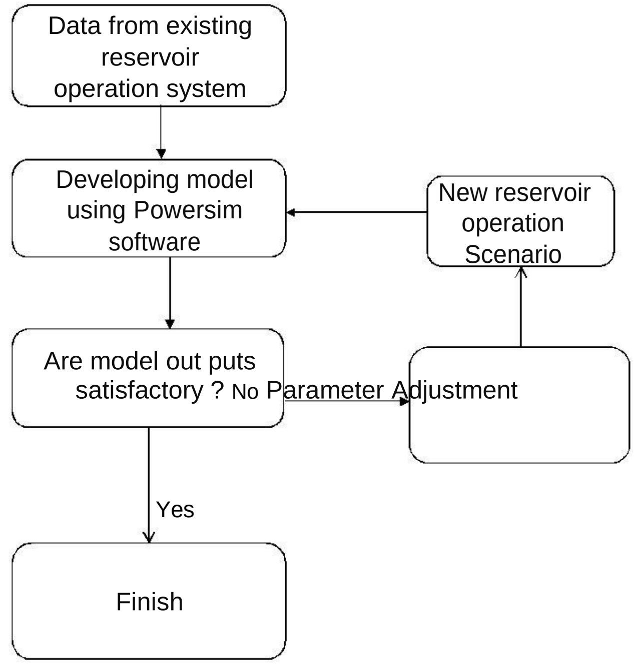

Figure 1. Flow chart of the developed model.

Model building

The main features of Melka Wakena Hydropower plant are a dam reservoir, power canal, Forebay, penstock and powerhouse. The model was developed carefully so that all the important features of the real system can be represented. Figure 2 presents the Powersim diagram used to model the plant system. In Figure 2, Inflow represents the monthly surface flow rate into the reservoir including precipitation over the reservoir while the Reservoir regulates the water. Reservoir Release represents the controlled water outflow rate from the reservoir into the power canal conveying water to Forebay. The flow rate through turbines was represented by Turbine Flow. Water Loss and Energy Production represent monthly estimated rate of water loss and produced energy respectively. In this model, calculation of dam overspill was incorporated. Detail seepage loss was not included but water loss other than evaporation loss was estimated as linear function of reservoir inflow. The discharge through turbine and turbine net head were considered but detail turbine characteristics were not included in the model. Turbine efficiency was incorporated into overall efficiency. The water level variation in the Forebay has been neglected and constant power head of 297 m has been used in all cases of simulation analysis.

The construction of the model has been done by defining variables and the relationships between variables. This has been done computing the following in logical procedures:

(1)Average reservoir storage for the month: For the first month, January, the initial storage has been estimated. Initial storage should be between the minimum and maximum storage values.

(2) Reservoir water level: It is given as a natural logarithmic function of reservoir storage.

(3) Reservoir surface area: It is given as a linear function of reservoir storage.

(4) Evaporation loss using reservoir surface area and evaporation rate data.

(5) Over Spill loss when reservoir storage exceeds dam capacity.

(6) Leakage loss by estimating as fraction of reservoir inflow.

(7) Total loss, summation of the losses indicated above.

(8) Reservoir release; Power and Energy Production: They have been computed using the equations given below.

Reservoir release

The release from reservoir to Forebay is determined based on continuity equation. The model first computes the release and then checks for the constraints incorporated in the model.

$$S_{t2} = S_{t1} + I_t - R_t - TL_t$$

Where:

S_{t1} is initial storage in the month t, S_{t2} is final storage in the month t, I_t is reservoir inflow in the month t, R_t is reservoir release in the month t and TL_t is total estimated loss during month t.

Power production, P_t in kw

$$P_t = g{*}Ef{*}H{*}Q_t$$

Where: g is acceleration due to gravity, Ef is overall efficiency, H is net head in m, Q_t is discharge through turbine in m^3/s

Energy production, E_t in kwh

$$E_t = P_t{*}_t$$

Where, $_t$ is time step in hours.

The important constraints incorporated in this model were reservoir storage capacity, turbine flows and over spill.

The Storage S_t, is given as

$$S_{min} < S_t < S_{max}$$

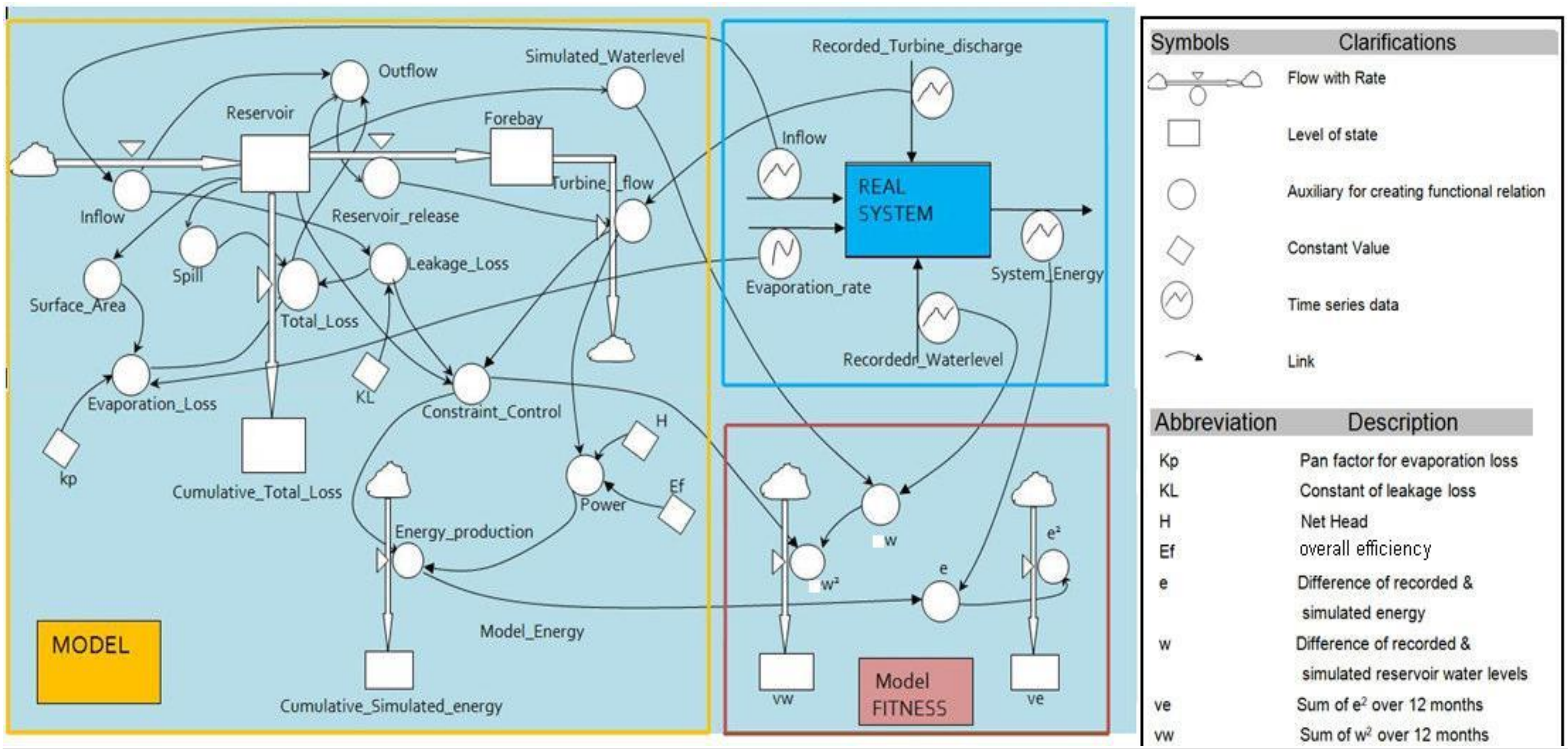

Figure 2. Powersim diagram of Melka Wakena Hydropower Plant System.

Where: S_{min} is the minimum storage limit while S_{max} is the maximum storage limit for the reservoir. The dead storage for the Melka Wakena is 157 MCM and its maximum capacity is 763 MCM.

The water flow Q_t, is given as

$Q_{min} < Q_t < Q_{max}$

Where: Q_{min} is the minimum water release when only one of the four turbines is operating and Q_{max} is the maximum capacity of conveyance system. Q_{min} and Q_{max} are 15 and 60 m^3/s, respectively.

The spill over the dam spillway, SP_t, is considered as $SP_t > 0$.

The input values of time serious data were expressed in the Powersim Model (Figure 2) . The average values of monthly data were given starting from January and ending in December. The precipitation over the reservoir is included into the reservoir inflow data. Figure 1 presents the flow chart of the algorithm used in this model.

Model fitting

The model was built with model identification method where the least square technique was adopted to fit the model (Figures 3a and b). In this case, the monthly average

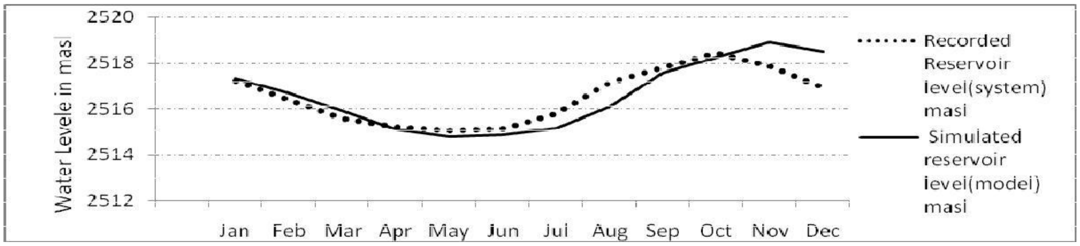

Figure 3a. Model fitting using data of recorded water elevation.

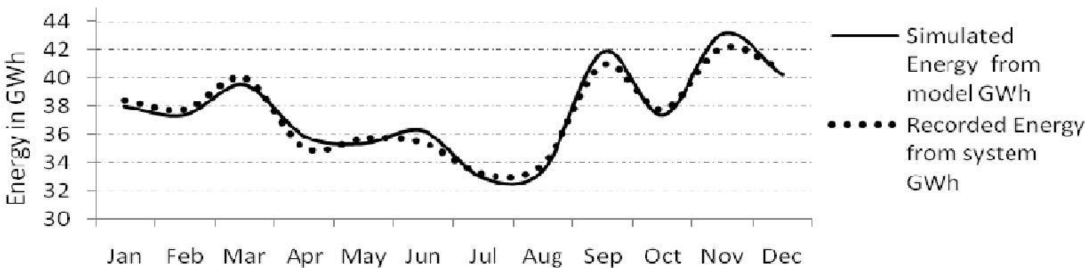

Figure 3b. Model fitting using recorded data of energy production.

energy production data and corresponding reservoir elevation data of 8 years were used. The model fitting process was done by minimizing annual sum of squared deviation (denoted by 've' in Figure 2) of the computed energy production from the recorded data and also by minimizing annual sum of squared deviation (denoted by 'vw' in Figure 2) of computed reservoir water elevation from recorded data of elevation (Figure 2). KL and Ef (Figure 2) were the two Model Calibration parameters used in the model fitting. KL is the constant of leakage loss estimation as a fraction of reservoir inflow. Ef is overall conversion efficiency of the plant.

Simulation analysis

In the detail analysis, the average monthly inflow of 36 years was used. Different simulations were carried out by changing the values of initial reservoir storage and acceptable reservoir release for power generation with the aim to obtain maximized yearly energy output with improved uniformity of energy production.

All simulations were done within the given limitation of reservoir capacity, water conveyance system capacity and spill over the dam spillway. In order to control the simulation outputs to be within required limits based on defined constraints, the auxiliary 'Constraint Control' was introduced (Figure 2). The functional relation satisfying the minimum and maximum limiting values was introduced in this auxiliary. This also helped to avoid unnecessary calculations and reduce run time

RESULTS AND DISCUSSION

From the model fitting process, the calibration parameters KL and Ef were determined to be 0.168 and 0.88 respectively. This significant value of KL indicated that there was considerable water lost without being used for power generation. This confirmed the fact exposed in the literature that the plant operates below design capacity. The estimated value of Ef, 0.88 is reasonable. It is the overall conversion efficiency of the plant with the existing installed turbines and generators. The model used this value in energy determination during simulation analysis.

The results of model fitting have been presented graphically (Figure 3a and b). Figure 3b shows that under the existing operation system the minimum energy production was in July and August, the rainy months in the area. The maximum production was observed in September and November. In October there was unexpected reduction of production in the existing operation system. This reduction may be due to less energy demand from this plant in October. But in the case of simulated energy production (Figure 3b) more energy was produced in October. This has been accepted with the assumption that there is increasing energy demand throughout the year in the country.

The optimized energy output was obtained from the detail analysis (Figure 4a). The yearly average energy production was found to be about 476.68 GWh (see Figure 4b). The annual total water loss was estimated to be 160 MCM out of which evaporation loss was about 28.57 MCM. The result of simulation analysis (Table 2 and Figure 4a) indicates that the uniformity of energy production was improved. The average monthly energy output was about 39.88 GWh throughout the year except for the month of June, the beginning of rainy season in Ethiopia, for which the result was 38 GWh. Figure 4(a) also indicates that in the existing system less energy production was observed in April, May, June, July and

Table 2. Main Outputs of the analysis and corresponding value from existing system.

Description	From existing system	From model analysis	Remark
Average annual energy production in GWh	450.71	476.68	Improved by 5.76%
As percentage of Annual average design Energy production (543GWh), %	83.01	87.79	Less than capacity
Average annual evaporation loss in MCM	46.33	28.57	Reduced by 38.33%
Maximum Reservoir water level in masl	2518.43	2514.32	Observed In October and November, respectively
Maximum monthly Energy in GWh	42.13	39.88	reduced
Minimum monthly energy in GWh	33.16	38	increased

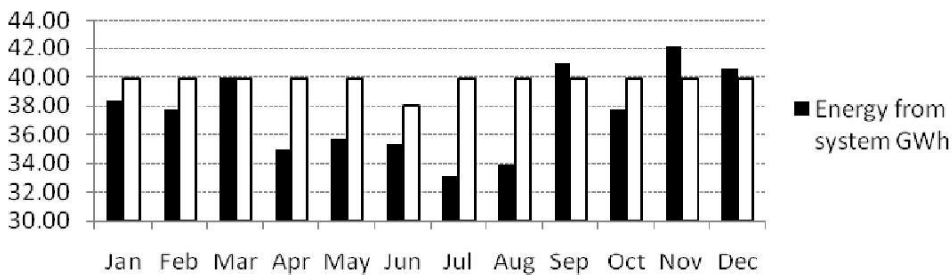

Figure 4a. Comparison of recorded system energy and simulated energy.

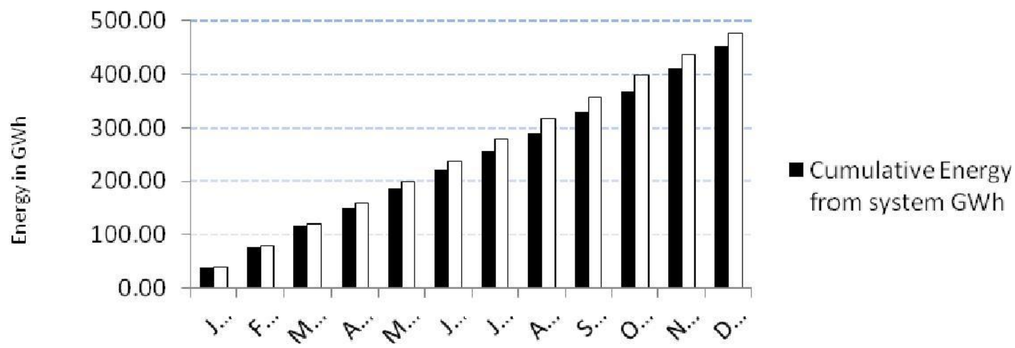

Figure 4b. Comparison of system energy and simulated energy.

August. This exposed the reservoir water for more evaporation loss. The simulated energy production is uniform throughout the year except for the month of June. In Ethiopia, June is the month in which the dry season gives place to the rainy season and for this month the simulated energy was less due to less water in reservoir (Figure 4a).

Figure 3b compares the recorded energy of real system and the simulated energy and it shows the increase of energy production. The optimum simulated energy output was increased by 25.97 GWh per year, which was the improvement of about 5.76% (Table 2). Even if energy production was improved, it was still below the yearly average production capacity of 543 GWh. The results indicated that the annual average energy productions, from the existing system and from the model analysis were 83.01 and 87.795% of the design capacity respectively (Table 2). The difference between the simulated annual energy and design capacity was 66.32 GWh. That means the optimum simulated energy was found to be below the design capacity by about 12.21%. The reason for this might be the reduction in reservoir inflow and water loss from the system. The reservoir inflow has been reduced by about 5% from the design reservoir inflow (827 MCM) (Bosona, 2004). The current study also indicated that there is considerable water loss from the plant system. Causes of this water loss should be investigated further by detail study of both surface and

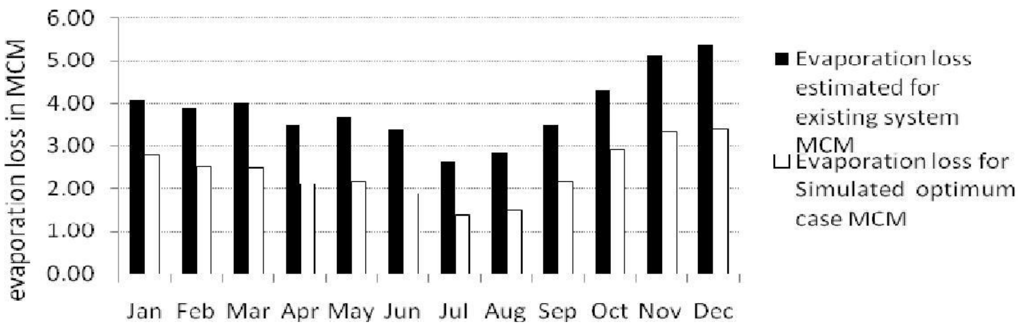

Figure 5. Comparison of estimated monthly evaporation losses.

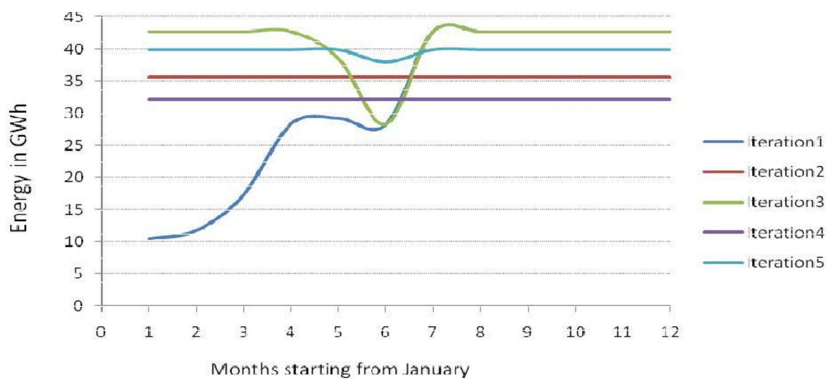

Figure 6. Simulated energy for 5 sample iterations.

ground water loss conditions.

Figure 5 indicates the reduction of evaporation loss from the reservoir. It was reduced throughout the year and more reduction was observed in November and December. It was reduced by 17.76 MCM per year, which is about 38.33% (Table 2). Many iterations were carried out during simulation analysis to obtain the best result according to our objective. Figure 6 illustrates the energy output of five sample iterations.

The improved Guide Curve (Figure 7) developed using this model indicates that the maximum water level in the reservoir was about 2514.32 masl while the Full Reservoir Level was 2522.6 masl. No spillage from the reservoir was observed during the analysis. This indicates that the large amount of the useful storage is empty throughout the year.

Conclusion

The developed dynamic simulation model using Powersim software could describe and simulate operations of the Melka Wakena Hydropower. Therefore Deterministic Dynamic Simulation Model built in Powersim software can be adopted to improve the operational guide curve of the reservoir in this power plant system. The simulation results indicated that the quantity and uniformity of energy production can be improved. Concerning the uniformity of energy production, the gap between maximum and minimum monthly energy production was reduced from 8.97 to 1.88 GWh. The average annual energy production was increased by 25.97 GWh while annual average evaporation loss was reduced by 17.76 MCM. Even if production improvement is possible using this model (with improved guide curve) still the plant operates below its design capacity by 12.21%. The reason for this might be the reduced reservoir inflow and water loss from the system. The detail water loss calculations were not incorporated in this simulation model due to limitation of data. Therefore, causes of this water loss should be investigated further by detailed study of both surface and underground water loss conditions.

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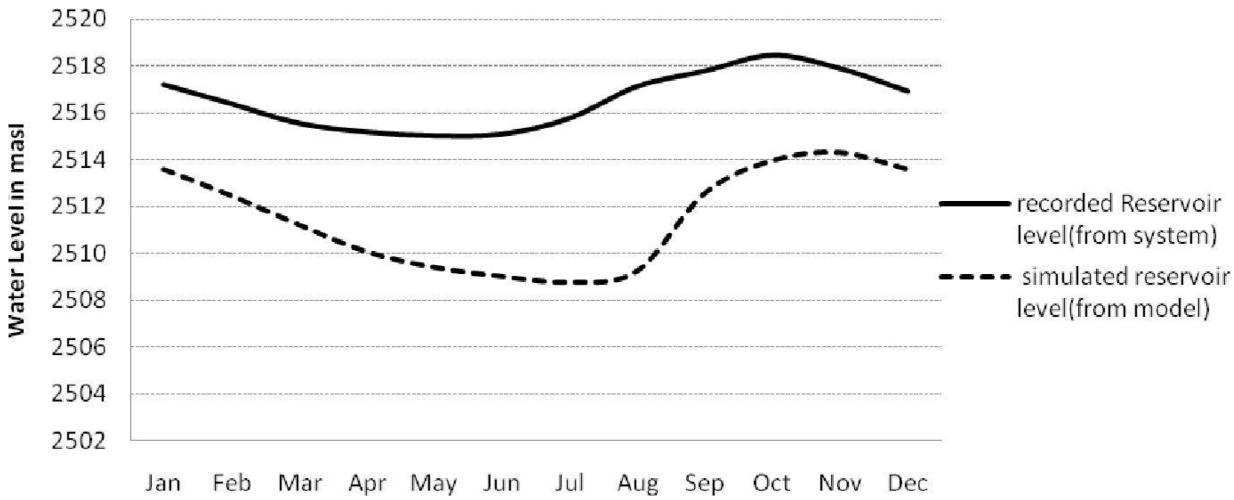

Figure 7. Existing and newly developed guide curves.

Technology.

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