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# Modeling of Cascade Dams and Reservoirs Operation for Hydropower Energy Generation

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ABSTRACT: Rapid regional growth and energy demands of the Ethiopia's government have driven plans to build cascade dams along the Omo Gibe river basin mainstream and its tributaries which exacerbate significant concerns of the availability of water for the downstream population of the basin. Present study attempts to apply decision support tool to improve reservoir operations for hydropower energy generation considering the existing water demand conflicts in the region. In order to achieve this purpose HEC-ResSim (reservoir simulation) model was used to simulate cascade dams and reservoirs operation to optimize water for hydropower energy production, flood management as well as environmental flows. The model was tried to represent the physical behavior of cascade reservoirs in the basin with its high speed hydraulic computations for flows through control structures, and hydrologic routing to represent the lag and attenuation of flows through the main and tributaries of the river. Hence, the model results indicate that the new reservoir operation rule selected for modelling of the cascade dams and reservoirs operation enhances average energy production of the designed reservoir operation systems of the basin by 28-45%. In addition, the hydrologic flood simulation results reveal that the new operation system will increase water availability in the dry season and decrease flooding in the wet season. Overall the study has determined the new reservoir operation system will evenly allocate and release the available water in real time during day-to-day and emergency operations throughout the year.

*Keywords: HEC-ResSim, Cascade dams & reservoirs, Omo Gibe river basin, Reservoir operation*

## 1 INTRODUCTION

Water resources management is a complex and varied topic that requires consideration of a broad range of social, economic and environmental interests. As Ethiopian's river basins water resources become increasingly stressed, effective tools for management become more important. One tool often used in water resources management is decision support systems. McKinney and Watkins (1995) define a decision support system as an integrated, interactive computer system, consisting of analytical tools and information management capabilities, designed to aid decision makers in solving relatively large and unstructured problems. Modelling of cascade reservoirs operation for multipurpose function is more challenging that comprises modelling of flow in the river, reservoir storage, and allocation of water through hydropower plants and other outlet groups. This paper deals with HEC-ResSim (USACE, 2007) reservoir simulation model, as tool to assist in evaluating existing and nearly completed projects reservoir operations, and conservation storage requirements of three hydropower plants (i.e., Gibe I, Gibe II and Gibe III) and to assess the influence of major reservoirs on flood flows at the downstream of Omo Gibe river basin. Well modelled reservoir operation aids an engineer or reservoir operators to have the general operation strategies to release water according to the current reservoir level, hydrological conditions, water demands and the time of the year. This can be achieved by improving the already established rule curves by the existing information, forecasted climate and hydrological conditions, and advanced computational technology. Therefore, it would be crucial to establish an analytic and more systematic approach to extend networked reservoir operation for single or multi-purposes rather than the traditional individual reservoir operation in order to increase reservoir's efficiency for balancing demands from different stakeholders.

## 2 DESCRIPTION OF THE STUDY AREA

The Omo Gibe basin is Ethiopian's second largest river system next to that of the Blue Nile, accounting for 14% of Ethiopian's annual runoff. It flows from the northern highlands through lowland zone to discharge into Lake Turkana at Ethiopia/ Kenya border in the south and is fed along its course by some important tributaries. The river system is a purely hydroelectric scheme including three power plants located on Gilgel Gibe and Omo rivers. The Gibe I dam is located on the Gilgel Gibe river, a small tributary of the main Gibe river situated aproximately 260 kilometres southeast of Addis Ababa. The project dates back to 1985 but it was effectively built between 1997 and 2003. The project consists of a 40 metre high dam which created a reservoir of 63 square kilometres, with an underground power house with three turbines. Gibe I is a conventional hydroelectric power plant with a capacity of 184 Megawatt (MW) and upgraded to 220MW (EEPCO, 2004). Gibe II Power Station is a hydroelectric power station on the Omo River. The power station receives water from a tunnel entrance 7°55′27″N and 37°23′16″E on the Gilgel Gibe River. It has an installed capacity of 420 MW. The Gilgel Gibe is a tributary of the Great Gibe river, known as the Omo river downstream of the bridge of the highway Addis Ababa-Jimma (EEPCO, 2006). Gibe II uses the water discharged by the first and has a gross head of 505 m. This new head is created by a waterway that bypasses about 110 Km of the two rivers (Gilgel Gibe and Omo). Gibe III Dam is an under construction 243 m high roller-compacted concrete dam and located in the middle reach of the Omo river. Once completed it would be the largest hydroelectric plant in Africa with a power output of about 1870 MW, thus more than doubling total installed capacity in Ethiopia from its 2007 level of 814 MW. The downstream area extends from the dam site down to Lake Turkana (EEPCO, 2006).

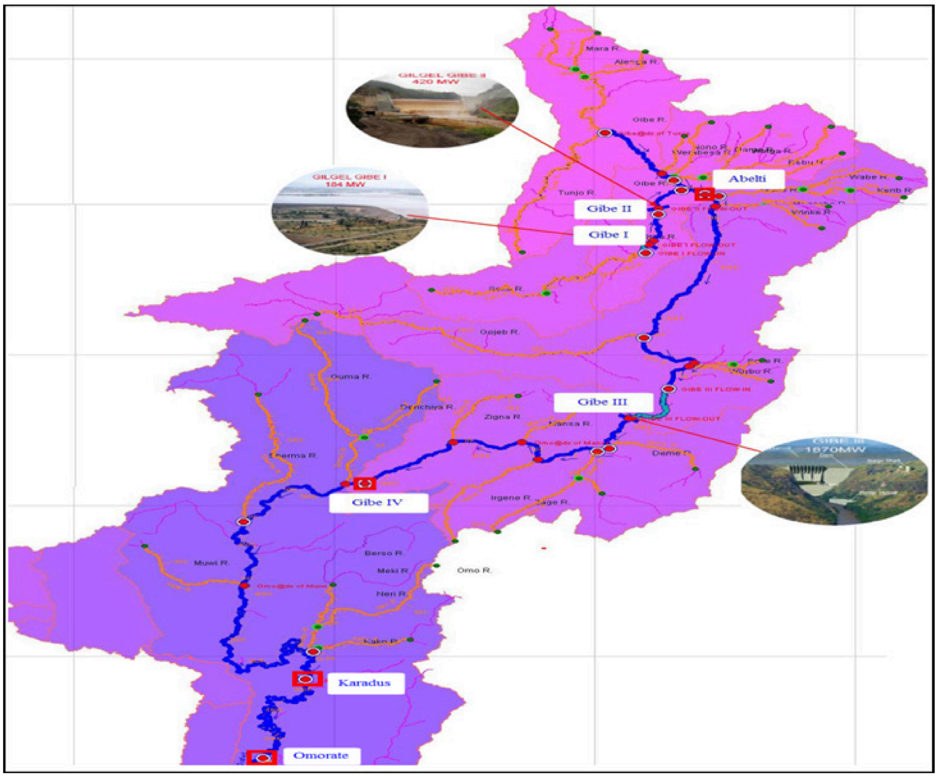

Figure 1. Layout of Omo Gibe river system, calibration and computation points, and location of dams

## 3 MATERIALS AND METHODS

### 3.1 *Approaches of HEC-ResSim model and data*

The model needs intensive data for simulation of reservoir operation and flow routing in river basin system. These data include time series data, physical and operational reservoir data. The time series data are observed and local flows on the main and tributaries of the river that include historical and forecasted flows. In this study, daily inflows at cascade reservoirs for the HEC-ResSim model setup were determined using SWAT model. SWAT is a physically based, continuous, long-term, distributed-parameter model designed to predict the effects of land management practices on the hydrology, sediment, and contaminant transport in agricultural watersheds under varying soils, land uses, and management conditions

(Arnold et al., 1998). A detail of the steps for SWAT model is omitted here and the reader is referred to Seyoum (2014). The ResSim program has three modules which are the watershed setup, the reservoir network definition and the simulation scenario management. The model development began with creation of watershed schematic which is defined through the development of a stream alignment that serves as the framework or skeleton upon which the model schematic is created. The second step in model development was the establishment of a reservoir network. A reservoir network represents a collection of watershed elements connected by routing reaches. The network includes reservoirs, reaches and junctions needed for the model and is where all the physical and operational data are entered and stored in the model. Finally the model development was completed by defining the three alternatives for two scenarios, and running simulations and analyzing results. With this approach, the model was calibrated and the best alternative was selected for modelling of the cascade dams and reservoirs operation.

### 3.2 *Reservoir simulation modeling*

Simulation modelling replicates the physical behaviour of a system on a computer and it is an abstraction of reality. The key characteristics of the system are reproduced by a mathematical or algebraic description. Simulation is different from mathematical programming techniques which find an "optimum decision" for system operation meeting all system constraints while maximizing or minimizing some objective (Yeh, 1985). In contrast, simulation models provide the response of the system to specified inputs under given conditions or constraints. Hence, simulation models enable a decision maker to test alternative scenarios (e.g., different operating rules) and examine the consequences before actually implementing them. Simulation models for the operation of reservoirs have been applied for many years (e.g., Emery & Meek, 1960, Hall & Dracup, 1970, Biswas, 1976, Stansbury et al., 1991, Huang & Yang, 1999; Ito et al., 2001, & Thorne et al., 2003). Many models are customized for a particular system; however, more recently, the trend has been to develop general simulation models that can be applied to any basin or reservoir system. For example, HEC-ResSim model has been designed and developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers specifically to perform Reservoir System Simulation. It is designed to perform reservoir operation modelling at one or more reservoirs for a variety of operational goals and constraints, including release requirements and constraints, hydropower requirements and downstream needs and constraints (HEC, 2007)

### 3.3 *HEC-ResSim reservoir simulation model*

HEC-ResSim was developed to aid engineers and planners performing water resources studies in predicting the behavior of reservoirs and to help reservoir operators plan releases in real-time during day-to-day and emergency operations (Klipsch & Evans, 2007). It is used to simulate reservoir operations including all characteristics of a reservoir and channel routing downstream. The program represents the physical behavior of reservoir systems through a combination of hydraulic computations of flows through control structures and hydrologic routing to represent the lag and attenuation of flows through stream segments. The model uses an original rule-based approach to mimic the actual decision-making process that reservoir operators must use to meet operating requirements for power generation, flood management and environmental release. Parameters that may influence the flow requirements at a reservoir include the time of year, the hydrologic conditions, and any simultaneous operations by other reservoirs in a system. The reservoirs designated to meet flow requirements may have conflicting demands and constraints on their operation. The model represents operating goals and constraints with an original system of rule-based logic that has been specifically developed to represent the decision-making process of reservoir operation (Klipsch & Evans, 2007). It also allows the user to define alternatives and run their simulations simultaneously to compare results. This increases accuracy and is unique among reservoir simulation models because it attempts to reproduce the decision making process that human reservoir operators must use to set releases.

## 4 RESULTS AND DISCUSSIONS

The objective of cascade reservoirs simulation was to select the best reservoir operation rule that optimize water management for hydropower energy generation, controlling of flooding and availability of water throughout the year for downstream users. Simulation was performed by defining three reservoir operation alternatives for two scenarios based on considering the past and future hydrologic condition and future expansion of the nearly complete project. Base on this fact the first scenario was simulated for the period of 2006-2013 configuring (Gibe I and Gibe II); and the second scenario was for the period of 2014-2031 that incorporates Gibe III in addition to the first scenario using the daily time series data.

### 4.1 *HEC-ResSim model calibration and verification*

The overall goal of calibration procedure was to check for flow routing through HEC-ResSim represents the real river morphology of the basin or not. The model calibration was done at two sections of the river namely: at the upper reach Abelti and at the middle reach Gibe III where the recorded observed data exist (Figure 1). The calibration targets are the daily observed and computed flows at stations between January 1, 1991 and December 31, 2000. The model simulates both regulated and unregulated flows while the unregulated flows were calculated without considering the operation of the reservoirs in the main channel and tributaries, and produces outflows as an output of the simulation on the basis of input flood routing parameters using Muskingum method. This procedure allowed calibration of the model parameters that control the local flows downstream of the reservoirs. For verification of the calibration quality of the model, two general assessment approaches were used; namely subjective and objective assessments. Subjective assessment is based on visual graphical comparison of the observed and simulated hydrographs. In contrast, objective approaches are based on calculating some quantitative statistical parameters, namely $R^2$ = the squared correlation coefficient between observed and simulated output and *NS* = the Nash-Sutcliffe efficiency. Therefore, the value for $R^2$ and NS parameter for the fit of Abelti's daily streamsflow are 0.93 and 0.89 respectively; and of Gibe III daily streamsflow are 0.92 and 0.83 respectively. Hence the statistical results indicate that the model unregulated flows are satisfactorily matched with observed flows at gaging stations. Also it may be noted from figure 2 and 3, the model can show good agreement between the shape of observed and unregulated flow hydrographs. From these two assessments, one can conclude that the model characterize the real behavior of flood routing in main and tributaries of Omo Gibe river basin.

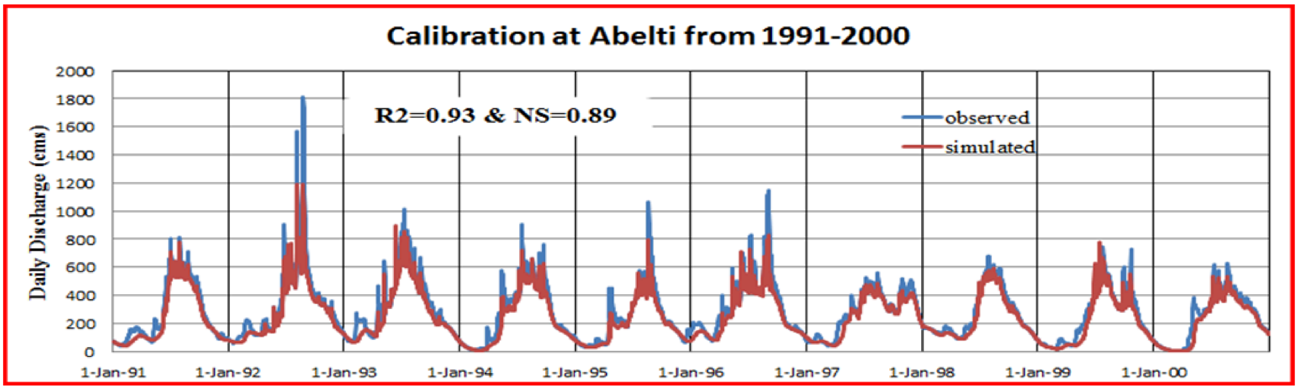

Figure 2. 1991-2000 observed and calibrated daily streamflow at Abelti station

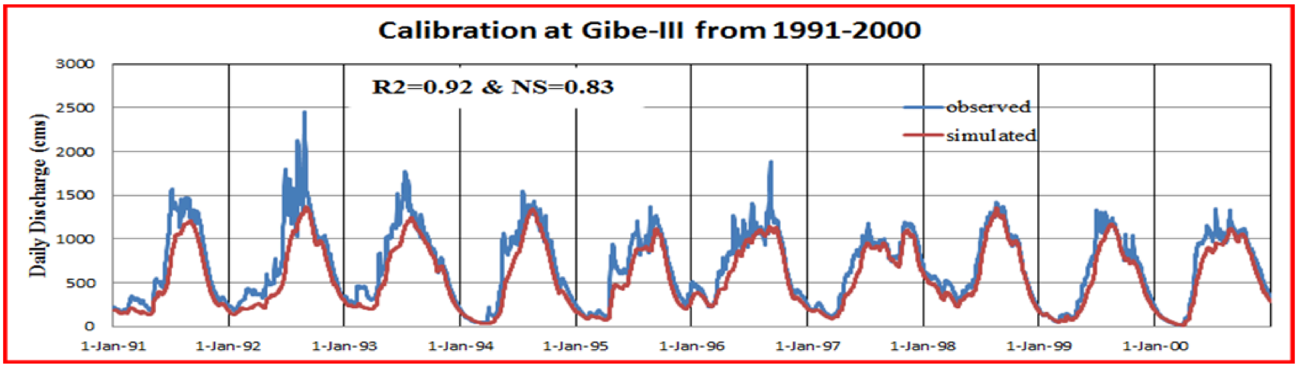

Figure 3. 1991-2000 observed and calibrated daily streamflow at Gibe III station

### 4.2 *Simulation results of scenario-one*

In this scenario operation zones (i.e., flood control zone, conservation zone, and inactive storage zone) are set or defined based on the data obtained from engineering design document of each project (EEPCO, 2003, 2004, 2006). Three alternatives were tested for each scenario to select the best reservoir operation which provides maximum power generation of the hydropower plant as the main objective function considering environmental and flood protection activities. In these cascade reservoirs, different hydraulic structures are configured in dam and reservoir pool namely power plant for generation of power, bottom outlet for environmental release, and diversion spillway for controlling flood. The allocation of water is sequential based on the priority given to the reservoir operation rule applied on the pool, dam and hydropower plant. Reservoir operation rules applied on dams and reservoirs pool for three alternatives are tandem reservoir operation (Alt1), hydropower schedule (Alt2) and hydropower guide curve (Alt3). Tandem operation is the method in HEC reservoir simulation model that used to analyze the reservoir operation in the system and the storage distribution among the reservoirs on the same stream. When a tandem reservoir system is defined, the model determines the amount of release from the upper reservoir in order that the downstream reservoir is operating towards a storage balance. For every decision interval an end-of-period, storage is first estimated for each reservoir based on the sum of the beginning of period storage and period average inflow value, minus all potential outflow volumes. The estimated end of date storage for each reservoir is computed to a desired storage that is determined by using a system storage balance scheme. The priority for release is then given to the reservoir that is furthest above the desired storage. When a final release decision is made, the end of period storage is recomputed. Depending on other constraints or higher priority rules, system operation strives for a storage balance such that the reservoirs have either reached their guide curve or they are operating at the desired storage [HEC, 2007]. The other two alternatives are hydropower rules (i.e., hydropower schedule and power guide curve) and these specify the minimum releases needed from a reservoir's power plant (or from the power plants in a reservoir system) to meet a power generation requirement and schedule. The desired release is a function of a plant's generation capacity, the hydraulic head, and the required energy. In the various hydropower rules, the generation requirement can be specified as a function of storage, season, or be directly specified as an external time series. The differences between these two rules are based on the specification or defining of the hydropower requirement. Hydropower schedule rule allows defining a regular monthly or user specified seasonally varying hydropower requirements while power guide curve rule allows defining a function that describes the hydropower generation requirement with respect to the available storage in the power pool. The power requirement must be described in units of % plant factor. Based on the input data requirements of the three operation rules applied for two reservoirs, different reservoir simulations were computed for scenario one. Table 1 depicts simulation results of both scenarios based on the three alternatives defined. From this table one can observe that alternative two gives higher value of average energy generation per simulation daily time step which is the main criteria to evaluate the three alternatives. Alterative two generates 2579.6 and 6776 MWh average energy per simulation daily time step for Gibe I and Gibe II respectively which are significantly larger value than the remaining two alternatives. Hence the hydropower schedule operation system was selected for modelling of the cascade reservoirs in the basin to optimize the water for hydropower, environmental and flood controlling in the cascade reservoir system for the simulation period of 2006-2013. The upper plots of figures 3 and 5 show graphical representations of reservoir levels with respect to time and depict computed reservoir, conservation, flood control, dam crest and inactive levels. As one can observe from these two figures, the computed reservoir level is within the required operating zone (i.e. conservation zone) to meet the monthly energy requirement and availability of water throughout the simulation period. The upper conservation level is the target level where ResSim try to keep while the computed level is the actual reservoir level calculated based on inflows and operation of the reservoir. The lower plots show the inflow and the outflow from the reservoir during the operation of the reservoirs with respect to the simulation period. Hence the guide curve (targeted) elevation using hydropower schedule rule is on the computed reservoir level.

Table 1. Summary simulation results of scenario I and II for three alternatives

| Scenarios | Scenario-One | | | Scenario-Two | | |
|---|---|---|---|---|---|---|
| Location/Parameter | Alt1 | Alt2 | Alt3 | Alt1 | Alt2 | Alt3 |
| Gibe I-Power Plant | | | | | | |
| Energy generated per time step (MWh) | 2371.6 | 2579.6 | 2529.1 | 2290.9 | 2432.8 | 2400.6 |
| Power generated (MW) | 98.8 | 107.5 | 105.4 | 95.5 | 101.4 | 100 |
| Gibe II-Power Plant | | | | | | |
| Energy generated per time step (MWh) | 5994.3 | 6776 | 6584.1 | 5827.5 | 6489.1 | 6383.6 |
| Power generated (MW) | 249.8 | 282.3 | 274.3 | 242.8 | 270.4 | 266 |
| Gibe III-Power Plant | | | | | | |
| Energy generated per time step (MWh) | - | - | - | 21468.2 | 22222.4 | 21697.5 |
| Power generated (MW) | - | - | - | 894.5 | 925.9 | 904.1 |

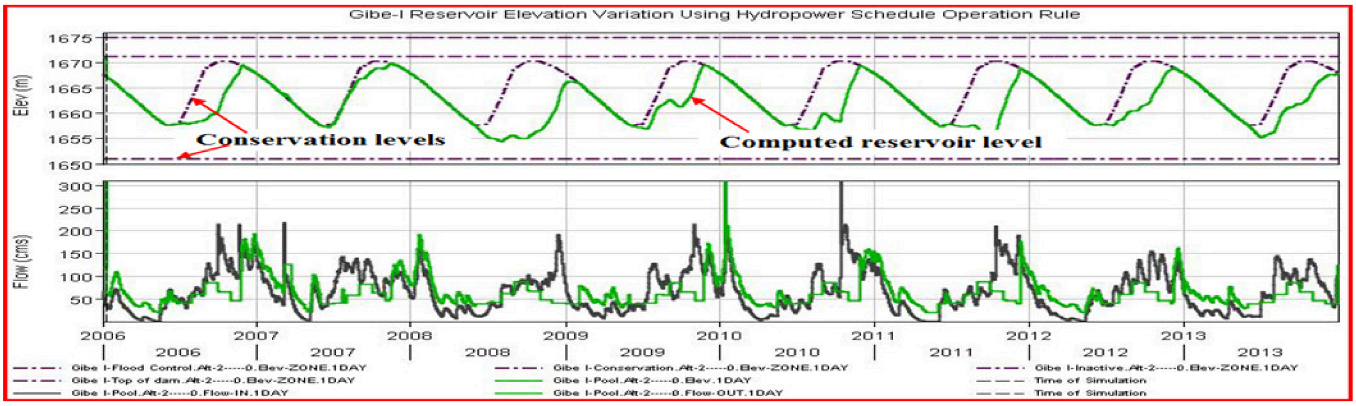

Figure 4. 2006-2013 Gibe-I reservoir levels-(upper plot): computed reservoir (green), conservation, inactive, flood control, top of dam (dark purple dotted lines), and Flows (lower plot): inflow (black) and outflow (dark green) hydrographs.

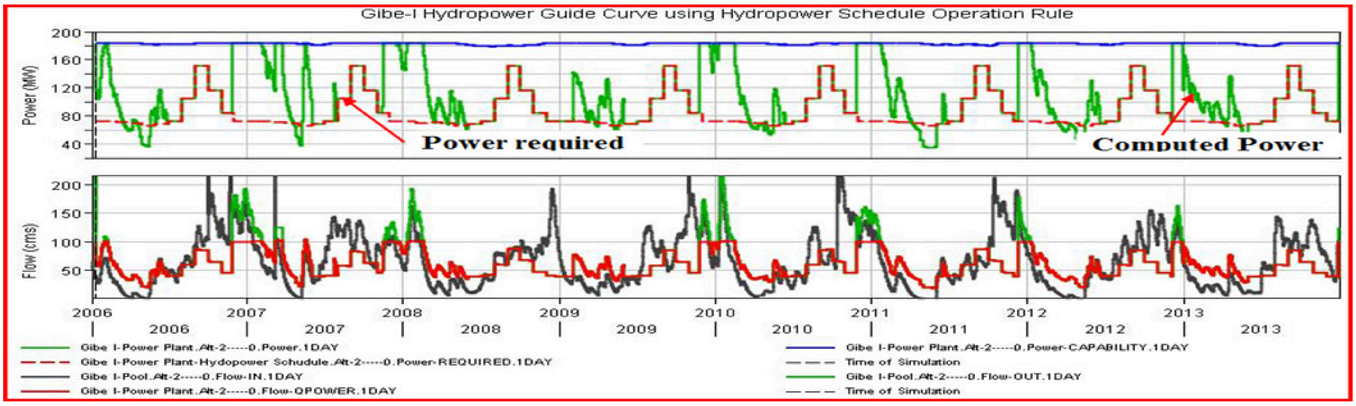

Figure 5. 2006-2013 Gibe I power plant operation (upper plot): power required (red), computed power (dark green), power capability (blue), and Flows: inflow (black), turbine flow (red) and outflow (dark green) hydrographs.

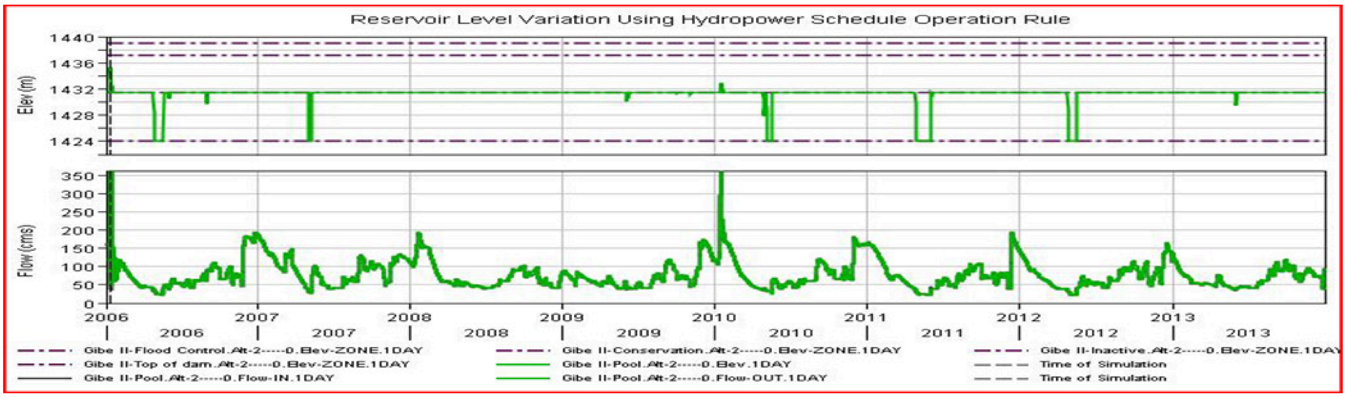

Figure 6. 2006-2013 Gibe-II reservoir levels-(upper plot): computed reservoir (green), conservation, inactive, flood control, top of dam (dark purple dotted lines), and Flows (lower plot): inflow (black) and outflow (dark green) hydrographs.

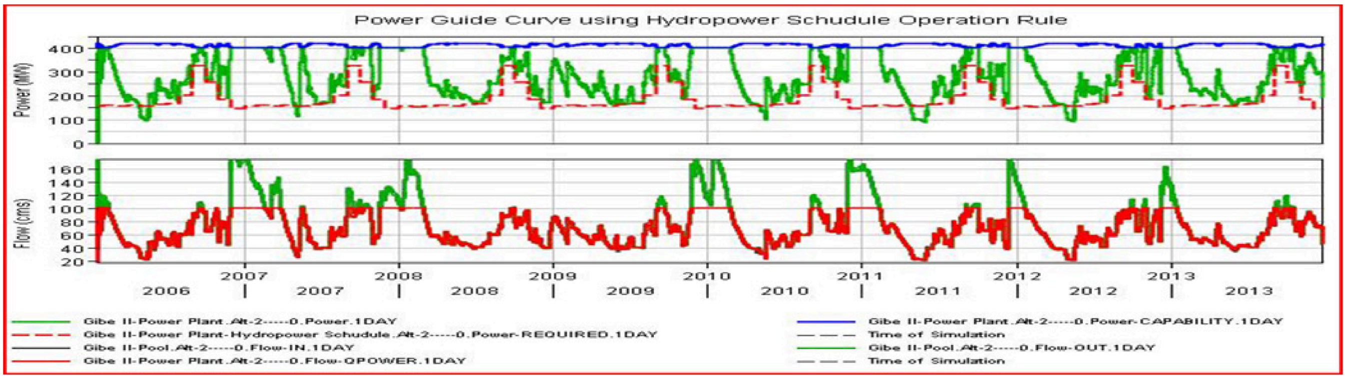

Figure 7. 2006-2013 Gibe II power plant operation (upper plot): power required (red), computed power (dark green), power capability (blue), and Flows: inflow (black), turbine flow (red) and outflow (dark green) hydrographs.

The maximum, minimum and average reservoir level computed for Gibe I as 1671, 1654 and 1662 m and for Gibe II as 1435, 1424 and 1431 m respectively. These results imply that there are good storage distributions and allocation of water for both reservoirs in the hydropower energy production system throughout the entire period. The levels of each reservoir have been observed almost in the conservation operational zone during the analysis period. The power required, power computed and power capabilities of the plant during the simulation period are shown in figure 5 and 7. In most of the simulation period, the computed power is equal or above the daily energy requirement applied from the design engineering document of each project. The average annual energy production using HEC-ResSim model were 942 and 2475 GWh/year for Gibe I and Gibe II respectively, and these energy production are more than the designed target power production studied by EEPCO-Saline. According to the engineering design document of the two projects, the average energy productions are 722 and 1635 GWh/year for Gibe I and Gibe II respectively, and these values were obtained from the energy calculated from the reservoir operational studies of 1967 to 1992 daily steamflows data (EEPCO, 2004). Hence, the new reservoir operating system using HEC-ResSim model improves the performance of both cascade hydropower plants approximately by 45%.

### 4.3 *Simulation results of scenario-two*

The second simulation scenario covers future period from 2014-2031 and considered nearly complete project-the third hydropower plant. In this system of operation, the reservoir network configuration considered Gibe III dam and its reservoir. The reservoir operations are defined by the same rules as scenario one (i.e., tandem, hydropower schedule and hydropower guide curve operation rules). In order to analyze the effect due to Gibe III dam and its reservoir, the model should be simulated with the same alternatives defined for the operation of reservoirs. Likewise the results of the model for hydropower energy generation for scenario two are summarized in table 1 above. From the table, the hydropower schedule operation system (Alt 2) generates 2432.8, 6489.1 and 22222 MWh energy per simulation daily time step for Gibe I, Gibe II and Gibe III respectively which are significantly larger value than the remaining two alternatives. Hence alternative two (i.e., Hydropower schedule operation rule) was selected for modelling of cascade reservoirs to optimize reservoir management in the Omo Gibe river basin for scenario two. Using this model, the maximum, minimum and average reservoir level computed for Gibe I as 1670.2, 1651 and 1660.92 m; for Gibe II as 1432.5, 1408 and 1430.96 m; and for Gibe III as 892, 855.39 and 868.12 m respectively. These results imply that there are good storage distributions and allocation among three reservoirs for the second simulation period of hydropower energy production system. The average annual energy production for scenario two are 888.56, 2370.09 and 8116.56 GWh/year for Gibe I, Gibe II and Gibe III respectively which are more than the energy production targeted on the engineering design documents of the three hydropower plants (EEPCO, 2004 and 2008). The targeted average energy production of the basin based on the engineering design document are for Gibe I is 722 GWh/year; for Gibe II is 1635 GWh/year; and for Gibe III is 6500 GWH/year (studied using the sequential streamflow routing (SSR) method for the period of 1954-2001 daily data- (EEPCO, 2006)). The results depict that the new rule-hydropower schedule operation improves the overall average energy production performance of the basin by 28%. Even though there are slight reduction in terms of reservoir levels and energy production from scenario one, the new rule increases the water management of the basin. This reduction of the reservoir levels and energy production is due to the effect of the input parameters i.e., river discharge in the cascade reservoirs from 2014-2031; this interns caused by the effect of climate change in the discharge of the river (Seyoum, 2014 and Bishaw, 2012).

## 5 SUMMARY AND CONCLUSIONS

The main aim of this study is to model cascade dams and reservoirs operation in the Omo Gibe river basin to satisfactorily simulate reservoirs operation for optimal water use of hydropower energy generation, environmental and availability of water at the downstream of the projects. It contributes for solving the challenge of water management problem of the study region through improving the individual reservoir operation to integrated operation system. Specifically, it is intended to inform policy makers, water resource managers, and other interested stakeholders to make effective and economically viable plans for sustainable future development in the Omo Gibe river basin. Reservoir operators must simultaneously meet water demands that rise from all stakeholders and other activities. Each of these demands imposes constraints on the storage and release of water from the reservoir, and needs and constraints often conflict with one another. Managing water in ways that best meet all demands including the needs of natural ecosystem is absolutely essential. For getting a real based logic for taking decision on water allocation in the basin, HEC-ResSim was applied for three dams and their reservoirs to maximize water for hydropower production, environmental protection, flood control, and the safety and structural integrity of the dam itself. Three alternatives were configured for two scenarios to model cascade dams and reservoirs operation so that the best reservoir operation rule that optimize the water release allocation was selected for modelling. The criterion for selection of the best reservoir operation is based on the simulation results of average energy generation per daily time step considering its effect on the availability of water at downstream flows. According to the simulation results obtained from the two scenarios, hydropower schedule operation rule shows maximum average energy generation, maximum availability of water distributed throughout the year, and better control of flood at the downstream of the river. Hence, hydropower schedule operation rule was selected to model cascade dams and reservoirs operation in Omo Gibe river basin. The power and energy generated from simulation model based on the best reservoir operation rule is summarized in Table 1. From the table, scenario two (time period from 2014-2031) gives relatively lower average power and energy generation compared to scenario one, and this is due to the effect of climate change on the input parameter, for this case inflow discharge at the entrance of cascade reservoirs (Seyoum, 2014 and Bishaw, 2012). In terms of percentage of energy generated in the basin using the new reservoir operation system to the previous studies by EEPCCO-Saline, the model enhances by 45% for scenario I and 28% for scenario II.  Overall, the study results show the model improves the performance of the plant to generate hydropower energy more than the expected design target of the previous reservoir simulation studies. Hence, this study has provided general operation strategies for reservoir releases according to the current reservoir level, hydrological conditions and the time of year and develops a unique power guide curve for all the three cascade hydropower plants.

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