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Maximization of hydropower generation from Hazelmere Dam in South Africa

Abstract

Harnessing more energy from existing water sources within the frontier of the country is germane in capacitating the South African Government's commitment to reduction of the country's greenhouse gas emissions and transition to a low-carbon economy while meeting a national target of 3 725 megawatts by 2030. This study aims to determine the amount of energy that can be generated from Hazelmere Dam on the Mdloti River, South Africa. Behavioral analyses of the Hazelmere reservoir were performed using plausible scenarios. Feasible alternative reservoir operation models were formulated and investigated to determine the best operating policy and power system configuration. The optimization models were formulated to maximize hydropower generation while keeping within the limits of existing irrigation demands. Differential evolution algorithm was employed to search feasible solution space for the best policy. Findings suggest that if the water resource in the dam is properly managed, about 558.54 MWh of annual energy may be generated from the reservoir under medium flow condition without system failure.

Keywords: hydropower, greenhouse gas, reservoir operation, differential evolution, behavioral analysis.
JEL Classification: Q50, Q55, Q57.

Introduction

The importance of the power sector in the development of a nation cannot be overemphasized. This sector is strategic in forging economic growth and infrastructural development. This calls for the development of improved strategies for generation, distribution and proper management of power in all countries of the world (Loucks and Bee, 2005; Salami, 2007). Hydropower is a renewable form of electrical energy generated from the free fall of water from a high elevation to a relatively lower elevation. Hydropower production involves the conversion of potential energy of stored water into electrical energy through combinations of hydraulic turbines and electric generators (Ajenifuja, 2009; SIDALA, 2010). Some benefits of hydropower include quick response to changing utility loads, relatively low operating costs and a low environmental pollution factor (Salami, 2007). According to Ajenifuja (2009), greenhouse gas (GHG) emission factors for hydropower plants have been found to be 30 to 60 times lesser than factors for fossil fuel generation in some instances. Presently, hydropower accounts for roughly 85 percent of renewable energy in the European Union and approximately 20 percent of global electricity. Development of half of the world's economically feasible hydropower potential could reduce GHG emissions up to 13 percent and global carbon dioxide pollution by up to 7 billion tons a year (Ajenifuja, 2009). Therefore, harnessing more hydropower from existing water sources is germane in minimizing GHG emissions and mitigating the undesirable effects of global climate change.

Recent results from expert analysis has shown that South Africa has moderate hydroelectric potential and establishing a number of small hydroelectric power plants around the country may help provide sustainable supply of energy in the future (SIDALA, 2010). Consequently, the South African government is in the process of authorizing independent power producer licenses. This aims to diversify the country's energy mix by bringing in renewable energy technologies especially small hydropower plants (< 10MW) to retrofit and contribute to a national target of 10 000 GWh of energy by 2013 (SIDALA, 2010). This study investigates the potential of Hazelmere Dam for generating electricity. The aim was to determine the amounts of monthly and total annual energy that can be generated from the reservoir based on turbines of various efficiencies for a plausible system configuration under medium a flow condition without system failure. The method adopted involved formulating optimization models to maximize hydropower generation while keeping within the limits of existing irrigation and domestic water demands. Estimating the amount of electrical energy that can be generated from the Hazelmere reservoir is relevant in capacitating the South African Government's commitment towards equity and poverty eradication. It is also germane to reducing the country's GHG emissions and transition to a low-carbon economy by 2030 (DOE, 2014; SIDALA, 2010).

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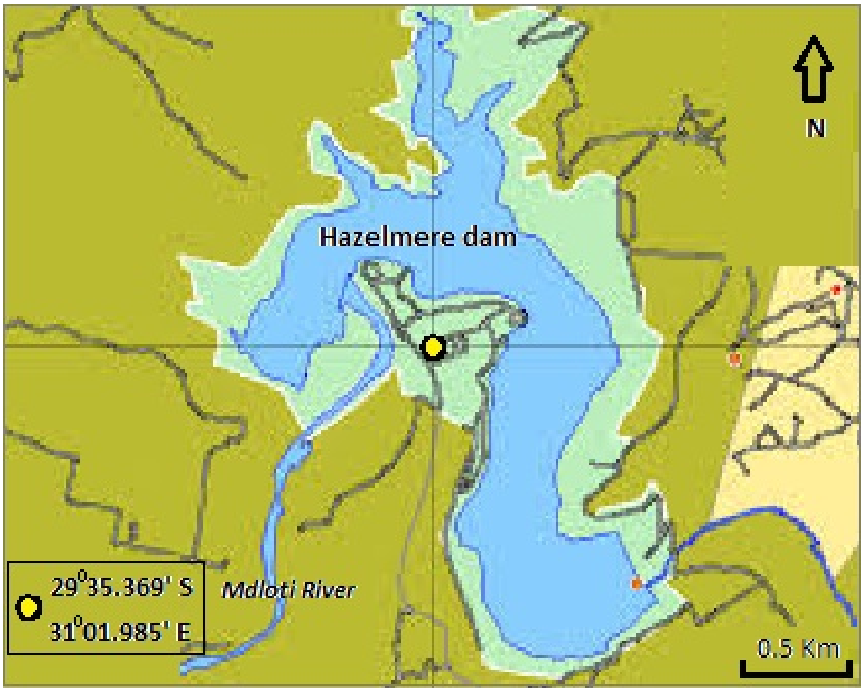
1. Methodology

This study determines the amounts of monthly and total annual energy that can be generated from Hazelmere reservoir based on turbines efficiencies of 75%, 85% and 90%. Optimization models were formulated to maximize hydropower generation within the constraints of existing abstractions, hydrological and system constraints. Differential evolution (DE) optimization method was adopted to resolve the optimization models. The methodology was applied for an operating season.

1.1. Study area. The study area is Hazelmere Reservoir on Mdloti River in South Africa. The Dam is a combined concrete gravity type dam and it resides in KwaZulu-Natal province of South Africa on latitude 29°36'1'' S and longitude 31°2'30'' E. It was established in 1977 primarily to serve for irrigation and domestic use. The reservoir has a capacity of about 17.858 million m^3 at an elevation of 85.98 mASL and a surface area approximately 1.81 square kilometers when full. The minimum reservoir elevation is 61.00 mASL which corresponds to a storage volume of zero Mm^3. Total catchment area contributing to flow in the reservoir is 377 km^2. Mean annual precipitation is 967 mm, mean annual runoff is 70.7 million m^3 while annual net evaporation is 1 200 mm. The main water use activities in the catchment are irrigation, dryland sugar cane, domestic use, commerce and industry. Figure 1 presents the general layout of the dam.



Source: adapted from: http://www.fishtec.co.za.

Fig. 1. Hazelmere Dam, South Africa

1.2. Proposed system configuration. An axial flow vertical Kaplan turbine with discharge of 40 m^3/s and a minimum operating head of 10m was adopted as suggested by (SIDALA, 2010). This type of turbine is useful in dams with low heads. The powerhouse is located at ground level with the turbines located at the minimum reservoir level (61 mASL). The penstock inlet is set at 71 mASL and specifies the minimum operating level for hydropower generation. This corresponds to reservoir storage of 7.15 Mm^3. The maximum reservoir volume (17.858 Mm^3), which corresponds to a reservoir elevation of 85.98 mASL, defines the maximum operating level. The power plant installed capacity is assumed to be 10 MW while the turbine efficiencies are varied between 75, 85 and 90 percentages.

1.3. Estimation of monthly reservoir inflows. Reservoir operations require that inflows into the reservoir over the planning period be estimated ahead of operations. Probability distribution models were employed to perform streamflow frequency analysis for the reservoir. Monthly reservoir inflow data for Hazelmere Dam was obtained from the Department of Water Affairs, South Africa. The nature of data is streamflow volume in mega liter (Ml) recorded for every month of the year. This was converted to mega cubic meter (Mm^3) for use in this analysis. A period spanning 19 years of data (1994-2013) was used for the analysis. The monthly series were ranked according to Weilbull's plotting position and the corresponding return periods were estimated. The series were evaluated using six methods of probability distribution functions, Normal, Log-Normal (LN), Pearson III, Log-Pearson type III (LP_3), Gumbel extreme value type1 (EVI) and Log-Gumbel (LG). The fit of the mathematical expressions obtained for each function were compared using Mean Relative Deviation (MRD) and Mean Square Relative Deviation (MSRD) statistics (Jou et al., 2009; Olofintoye and Adeyemo, 2012; Olofintoye and Salami, 2011). The best model for each month were used to estimate medium flows into the reservoir. Operating a reservoir without failure under a medium flow condition suggests that the reservoir will perform reliably at least 75 percent of the time (Scott and Smith, 1997).

1.4. Development of reservoir storage relationships. *Storage relationships are useful in computation of reservoir storage head and surface area necessary for estimation of generating head for hydropower and lake evaporation. In this study, linear relationships were developed to model the storage-elevation and storage-area relationships since the reservoir is small (capacity <50Mm^3)* (Salami, 2007).

1.5. Model formulation. DE was applied to optimize the operation of Hazelmere reservoir in a season (May to April). The dam was operated under a medium flow condition. The full capacity of the reservoir (17.858 Mm^3) was used as the starting storage for the reservoir. The decision date for reservoir operation in South Africa is May 1 when reservoir operating analysis is undertaken to decide how the reservoir should be operated in the coming year (Adeyemo and Olofintoye, 2014; Mugumo, 2011).

1.5.1. Decision variables and objectives. The main aim of the study was to determine the monthly water releases for hydropower generation at the dam while meeting the existing water demands on the dam. The existing water demands for irrigation, domestic and other uses were obtained from DWA and held as constrain that must be satisfied. The decision variables in this study are the monthly Turbine releases for hydropower generation *RTurbine* (Mm^3) and the existing monthly water abstractions from the dam *RExisting* (Mm^3). The objective of the reservoir operation optimization problem was formulated as:

Objective: Maximize total annual hydropower generation

Annual hydropower generation is maximized to generate electricity for the citizens at a cheaper cost. Equation (1) is used for maximizing energy generation from reservoirs (Ajenifuja, 2009; Loucks and Bee, 2005; Salami, 2007):

Maximize

$$Hp_{Total} = \sum_{t=1}^{12} 2.725 \times RTurbine(t) \times H(t) \times \varepsilon; \quad t = 1,2,...,12, \tag{1}$$

where Hp_{Total} is total annual hydropower generation over the operating period in megawatt hours (MWh). *RTurbine(t)* is the volume of water released through the hydropower turbines during month *t* in mega meter cube (Mm^3), ε is the turbine efficiency in converting the mechanical energy of water to electrical power, this is varied between 75, 85 and 90%. *H(t)* is the average hydropower generating head in month *t* in metres (m). *H* is specified as the vertical distance between the water surface elevation in the reservoir that is the source of the flow through the turbines and the maximum of either the turbine elevation or the tailwater elevation (Loucks and Bee, 2005).

1.5.2. Problem constraints. The single objective reservoir optimization problem of maximizing total annual hydropower generation at the dam is subject to the following constraints:

Constraint 1: Mass balance equation

The storage continuity equation defining the relationship between inflow and outflow variables at the reservoir site must be satisfied. This is presented in equation (3) (Loucks and Bee, 2005; Salami, 2007).

$$S(t+1) = S(t) + Q(t) - E_{net}(t) - R(t) - Ls(t), \tag{2}$$

where $R(t) = RExisting(t) + RTurbine(t)$; (3)

$$E_{net}(t) = P(t) - E(t); \tag{4}$$

$$Ls(t) = 0; \tag{5}$$

where *S(t+1)* is the reservoir storage at the end of month *t*, *S(t)* is the storage volume in the reservoir at the beginning of month *t*, *Q(t)* is the streamflow into the reservoir during month *t*, *P(t)* is precipitation on the reservoir surface during month *t*, *E(t)* is gross evaporation from the reservoir surface in month *t*, *Ls(t)* is seepage loss in month *t*, *RExisting(t)* is the existing water demand in month *t*. All variables are measured in volumetric units of mega cubic metres (Mm^3). Seepage losses are assumed to be negligible in this study.

Constraint 2: Limit on reservoir releases

The values of monthly releases through the turbines and other water outlets must lie between the minimum and maximum releases allowed through the outlets. Existing water demand is not maximized in this study but held as a constraint that must be satisfied. The constraints on the reservoir releases are presented in equations 6 and 7:

$$RExisting(t) = DExisting(t) \tag{6}$$

$$DTurbine(t) \le RTurbine(t) \le CTurbine(t) \tag{7}$$

where DExisting(t) and *DTurbine(t)* (Mm^3) are monthly existing demands and turbine demands respectively. C*Turbine(t)* (Mm^3) is the discharge capacity of the turbines in month *t*.

Constraint 3: Limits of reservoir storage

The monthly reservoir storages are allowed to vary between the minimum and maximum operating levels for hydropower generation. This constraint is specified in equation (8):

$$S_{min} \leq S(t) \leq S_{max}, \quad (8)$$

where S_{min}(Mm^3) is the minimum operating storage volume and S_{max}(Mm^3) is the reservoir capacity.

Constraint 4: Sustainability constraint

For the operation of the reservoir to be sustainable, the storage at the end of the operating period must not be less than the starting storage. This constraint is presented in equation (9):

$$S(13) \geq S(1), \quad (9)$$

where *S*(13) (Mm^3) is the storage volume at the end of the operating period which also represents the starting storage at the beginning of the next operating season. *S*(1) (Mm^3) is the storage at the beginning of the operating period.

Constraint 5: Limit on hydropower plant capacity

The maximum electrical energy that can be produced from a hydropower generating plant at any time is limited by installed plant capacity *P* (MW) and the plant factor *f*. The total energy produced (MWh) during any period cannot exceed the product of the plant factor *f*, the number of hours in the period *h* and the plant capacity *P*, as defined in equation (11) (Loucks and Bee, 2005, Salami, 2007):

$$Hp(t) \leq (Hp_{max}(t) = Ph(t)f) \quad (10)$$

$Hp_{max}(t)$is the maximum hydropower that can be generated in month *t* in megawatt hours (MWH). *Hp(t)* (MWh) is hydropower produced in month *t*.

2. Results and discussion

The reservoir operation optimization problem of maximizing annual hydropower production was solved using DE. Figure 2 depicts the hydropower generated for 75, 85, and 90% turbine efficiencies.

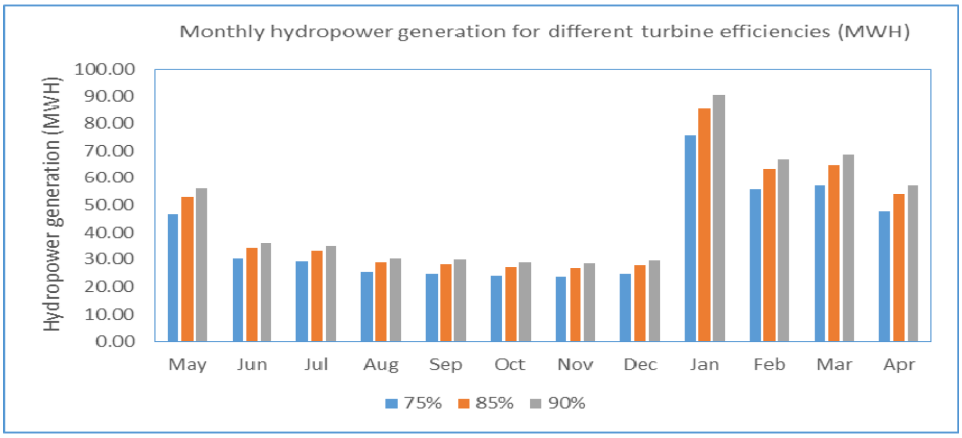


Fig. 2. Monthly hydropower generation for different turbine efficiencies at Hazelmere Dam

The findings in this study indicate that, in general, the DE algorithm performed well in finding optimal solutions to the problem stated. In a single simulation run, DE found solutions that provide optimal monthly water allocation for hydropower generation at the dam. Results of analysis show that it is possible to generate hydropower from the dam while still meeting the existing water demands on the dam. Figure 2 shows that the maximum hydropower potential is during the peak of summer in January while the minimum is in November. A total of about 91 MWh of power can be generated in January using a turbine of 90% efficiency while roughly 86 MWh and 75 MWh may be generated using turbines with efficiencies of 85% and 75% respectively. In November, 28.6 MWh can be generated by employing a turbine with an efficiency of 90%. About 27 MWh and 24 MWh may be produced by employing turbines with efficiencies of 85% and 75% respectively. A total annual energy of 558.54 MWh may be generated when using a turbine efficiency of 90% while 527.51 MWh and 465.45 MWh may be produced by employing turbines with efficiencies of 85% and 75% respectively.

Results of analysis in this study indicate that under a medium flow condition it is possible to generate hydropower from the dam while meeting all existing water demands on the dam without failure of the system. This suggests that the hydrology of the dam can sustain its current water demands and provide annual hydropower up to 527.51 MWh under the prevailing climate situation without excessive storage depletion.

Conclusion

Reservoir behavioral analysis was conducted to inspect the feasibility of generating hydropower from the Hazelmere reservoir under normal flow conditions. Optimization models were formulated to maximize hydropower generation from the dam. DE was employed to resolve the formulated models within the confines of the system constraints. It was found that 527.51 MWh of annual energy may be generated from the dam without system failure. Storage was maintained above critical levels while the reservoir supplied the full demands on the dam throughout the operating period indicating that the system yield is sufficient and there is no immediate need to augment the system.

Generating hydropower from the dam will provide electricity for the citizens at a cheaper cost. This aligns with the South Africa Government's commitment towards poverty eradication and reduction of the countries' greenhouse gas emissions to conform to international standards and reduce the country's contribution to anthropogenic global climate change (SIDALA, 2010). The methodology suggested in this study provides a low cost solution suitable for the sustainable operation of the Hazelmere dam and other similar dams in South Africa.

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