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Application of Conceptual Model in Developing the Jangwani Mini-Hydropower Plant in Ruvuma Region, Tanzania

Zacharia Katambara
Mbeya University of Science and Technology,
P.O. Box 131, Mbeya, Tanzania
Email: zkatambara1@gmail.com
Phone No.: +255756662009

Abstract

The Seventh Sustainable Development Goal is on ensuring access to affordable, reliable, sustainable and modern energy. The promotion and the use of renewable energy sources is inevitable. Within the spectrum of renewable energy sources, there are the mini-hydropower plants which have been reported to have the potential to provide for rural electrification. The existence of reliable flowing water necessitates the investment in mini hydropower for off-grid systems. To prove the viability of such schemes, ahydrological analysis of the Mtandazi River was conducted. The Australian Water Balance Model, a conceptual model, was used to model the stream flows using the California Method. The results suggest that for 95% exceedance, the flow is 1.62 m^3/s*. The flows will enable the installation of the Jangwani mini-hydropower plant to generate 226.7 kW of electricity in Ruvuma Region, Tanzania. The study recommends for the conservation of the catchment for the sustainability of the flows.*

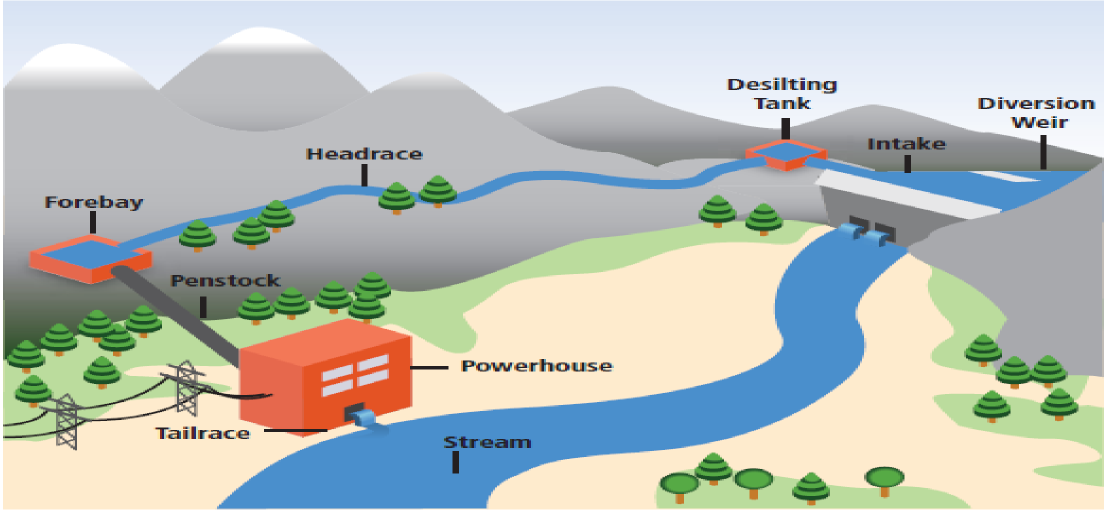
Key words: California method, stream flow, mini-hydropower, rural electrification

1.0 Introduction

The demand for energy is constantly increasing due the increase in population and the associated socioeconomic activities (Khandekar et al., 2015). On the other hand, the United Nation's Seventh Sustainable Developments Goal is to ensure access to affordable, reliable, sustainable, and modern energy. Among the affordable and reliable sources of energy is renewable energy, whichsupplies12.9% of energy consumption globally (IPCC, 2012).The availability of electricity has the potential to catalyse societal change by providing opportunities for a new range of activities and services (Ahlborg and Sjöstedt, 2015).

Owusu and Asumadu-Sarkodie (2016) reviewed the renewable sources of energy to include hydropower, biomass, geothermal, direct solar, wind, wave and tide as well as their associated technologies. For the hydropower plants, Elbatran et al. (2015) and Tamrakar et al (2015) provided two categories of classification which are technology based and capacity (power) based. The technology based include dammed reservoir, run of river, pumped storage, in stream and vortex gravitational energy. The capacity based ranges from large (>100MW), medium (15-100MW), small (1-15MW), mini (100kW-1MW), micro (5-100kW) and Pico (<1kW) hydropower plants (Tamrakar et al., 2015, Singh and Upadhyay 2014, Kaunda et al. 2012).Normally, the nature of the terrain necessitates for the installation of run-of river mini-hydropower. Tamrakar et al., (2015) indicated that a mini hydropower plant can either be a stand-alone power schemes or feeding into the grid. Figure 1 shows a typical run-of-river mini-hydropower plant with basic components which include water intake structure (e.g., weir and desilting tank), headrace, forebay, penstock, turbine, mechanical power transmission system to generator, generator, control system and electricity transmission system to load centres.

Figure 1
A Typical Run-Of-River Mini-Hydropower Plant (IPCC, 2012)

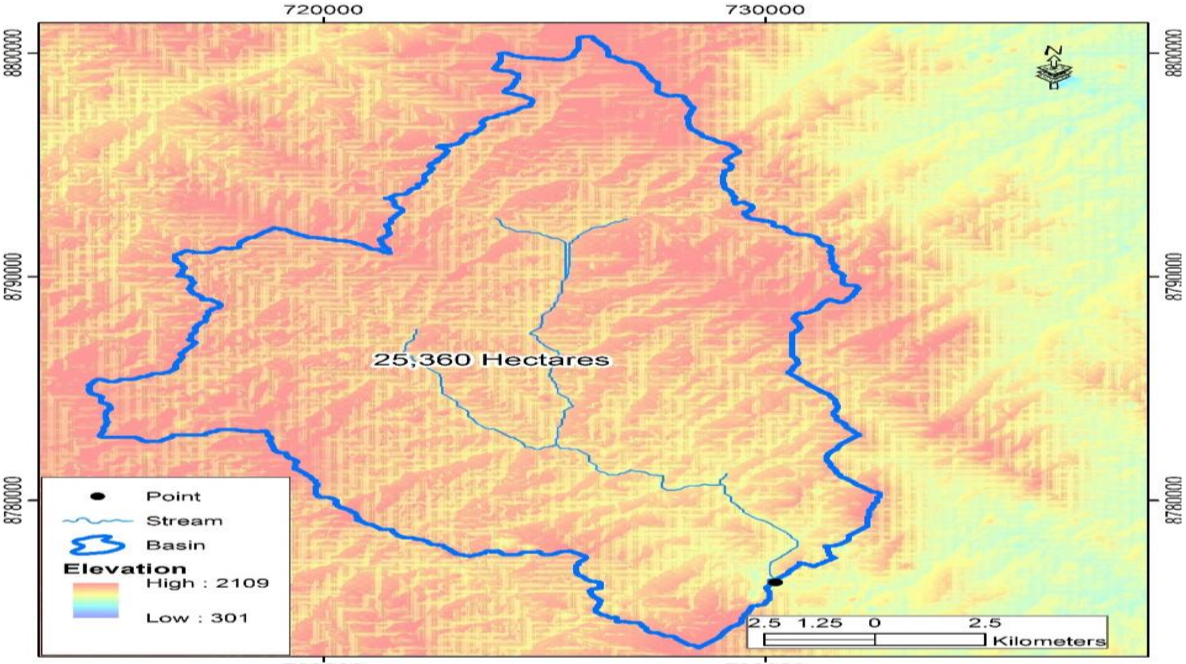


The reliability of the electricity generated by mini hydropower depends of the constant flowing water. Several studies on hydropower plant have been done. For instance, Hadjerioua et al (2016), studied the development of small hydropower on irrigation canals and applied the frequency duration curve to understand the hydraulic conditions of the site for a999kW power plant. Chuenchooklin (2006) used records from a nearby site with low flow of 0.5m^3/s to develop a 1.116kW power pico-hydropower plant for farming village in Thailand. For adequate potential head and constant flow rate, Sopian and Razak (2015) noted that a low-cost cross flow turbines for pico hydropower plants can provide three times enough power compared to the one provided by solar panels. Khandekar et al. (2015) applied the fuzzy axiomatic design principles based on trapezoidal fuzzy membership function to analyse the feasibility of a small hydropower plant and found it to be effective in accounting for impreciseness in the data. Tamrakar et al. (2015) investigated the opportunities of installing a hydropower plant in a sewerage system after wastewater treatment plant and the produced energy has the potential to meet the energy needs of approximately 35,000 homes. Khan and Badshah (2014) designed and analysed the cross flow turbine of micro hydropower plant for sewage water and the analysis proposed a safe and efficient turbine. Considering the advantages associated with hydropower and with the fact that the Mtandazi River is ungauged, this study applied catchment rainfall-runoff modelling to create river flows from meteoroidal data as discussed by Ndiritu and Daniell (1999) and frequency duration curve to understand the hydraulic of the River for the development of Jangwani mini-hydropower plant in Ruvuma Region, Tanzania.

2.0 Description of the Delineated Catchment Upstream of the Proposed Site

The positioning of the mini-hydropower among other issues requires consideration on the reliability of the flows and the potential head to drive the turbine. Mtandazi River is an ungauged River and therefore the river flows need to be created using a rainfall-runoff model. The knowledge of the catchment area where the complex process of converting rainfall to runoff on land occurs (Ndiritu & Daniell, 1999) is required. Several approaches of establishing the catchment exists, but the commonly used approach is the use of digital elevation model in geographical information system software to delineate the catchment. This approach was applied in this study. The delineated sub-catchment is located in a semi-arid region in Ruvuma Region and covers an area of approximately 253.6 km^2 (Figure 2). The sub-catchment is drained by Mtandazi River. The altitude ranges from above 400m to below 2100m above mean sea level. The outlet of the catchment is where the head works and the penstock originates for the proposed mini hydropower.

Figure 2
Delineated Catchment of the Mtandazi River



3.0 Data and Method

3.1 Hydrologic Model

Several hydrological models exist today and can be classified into three main categories namely black box, conceptual and physically based models (Chen & Adams, 2006; Ndiritu & Daniell, 1999; Rajurkar et al., 2004). Black box models are data driven models are preferred in situations where understanding of the perceived processes is not required and are based on heuristic approaches such as the artificial neural network (Kagoda et al., 2010) and fuzzy inference system (Katambara & Ndiritu, 2009). On the other hand, conceptual models emanate from perceived and known catchment processes represented by storages that are linked to each other in a simplified manner (Ndiritu & Daniell, 1999). These models can be used for evaluating various scenarios and have the potential to improve the model performance through model structural adjustment (Chen & Adams, 2006, Fenicia et al., 2008) and implementation automatic calibration algorithms (Ndiritu & Daniell, 1999). Physically-based models are deduced from physical phenomena and they represent the complex reality of the processes. The processes relationships are deduced from field measurements and the models are not calibrated. Example of these model include ACRU water budget model (Schulze, 1995) and the MIKE SHE model (Refsgaard et al., 1995).Their use in real world problems is cursed by the limited availability of the data (Ndiritu & Daniell, 1999). The need to incorporate catchment characteristics while there exists limited data merited the use of conceptual model, the Australian Water Balance Model (AWBM) (Boughton, 2004, Boughton & Chiew, 2007).

3.2 Australian Water Balance Model

The commonly applied Australian Water Balance Model (AWBM) (Boughton, 2004, Boughton & Chiew, 2007) was used to generate the stream flow of the ungauged sub-catchment. The model requires daily rainfall and evaporation data. Structurally, the model generates the flow through five conceptual stores (3 for partial area that generate excess runoff and 2 for surface store and base flow). This arrangement necessitates the model to simulate delayed surface runoff for medium and large catchments (Katambara, 2013). The water balance for each store is computed independently and the excess contributes to runoff and base flow. The applied water balance equation is given as:

$$S_{k,t+1}=S_{k,t}+R_t-E_t \tag{1}$$

where S is the storage of store k (1 to 3) at time step t, R is the rainfall and E is the evapotranspiration. When the amount of rainfall received is higher than the storage capacity $S_{k,t+1}$, the excess rainfall is generated. When runoff occurs part of it contributes to base flow. The shuffled complex evolution (Duan et al., 1992) was used to optimise the parameters, the root mean square error was used as an objective function and the Nash-Sutcliffe and the correlation coefficient were used as the model performance measures (Katambara & Ndiritu, 2009). The values range from zero to one and a perfect match between simulated and observed is one (Moriasi, et al., 2007).

3.3 Data Used

The data used in the generation of the stream flow include a 30m digital elevation model (DEM) from ASTER Global Digital Elevation Mode, 10 year monthly average daily temperature, 20 year daily rainfall from 1993. Spots of stream flow data recorded in the month of March and October from the year 2005 to 2013 at a gauging station located upstream of the proposed site was used to validate the obtained parameters.

4.0 Methodology

The methodology involved:
Catchment delineation: The processes of establishing the hydrological catchment boundaries so as to identify the runoff contributing area as well as the river network was done using a 30m digital elevation model (DEM) that was processed by applying the ARCSWAT extension of ArcGIS. The established catchment boundary as well as the river network is shown in Figure 2. The established area and river networks represent the actual situation of the intended study and the approach is similar to that presented in Katambara et al., (2013).

Potential Evapotranspiration: The potential evaporation was estimated using the Hargreaves Method; a temperature based evaporation model. This is similar to the approach applied in the Pangani River Basin (Moges et al., 2003).

Identification of suitable parameters of AWBM: The AWBM was calibrated using the data obtained from Mbarali Catchment, which has been observed to have similarities including annual rainfall. Therefore, the obtained parameters were considered adequate for the catchment. Verification of the flows using the spot flow observation was done.

Simulation of Mtandazi River flows: The model was set to simulate the flows of the delineated catchment and thereafter a frequency duration curve was developed.

Power generation: The topographical survey conducted at the site indicated that the potential flow head of the water was 16m. The power potential for the site was evaluated at a flow corresponding to 95% of the frequency duration curve (FDC) of Mtandazi River using the equation below

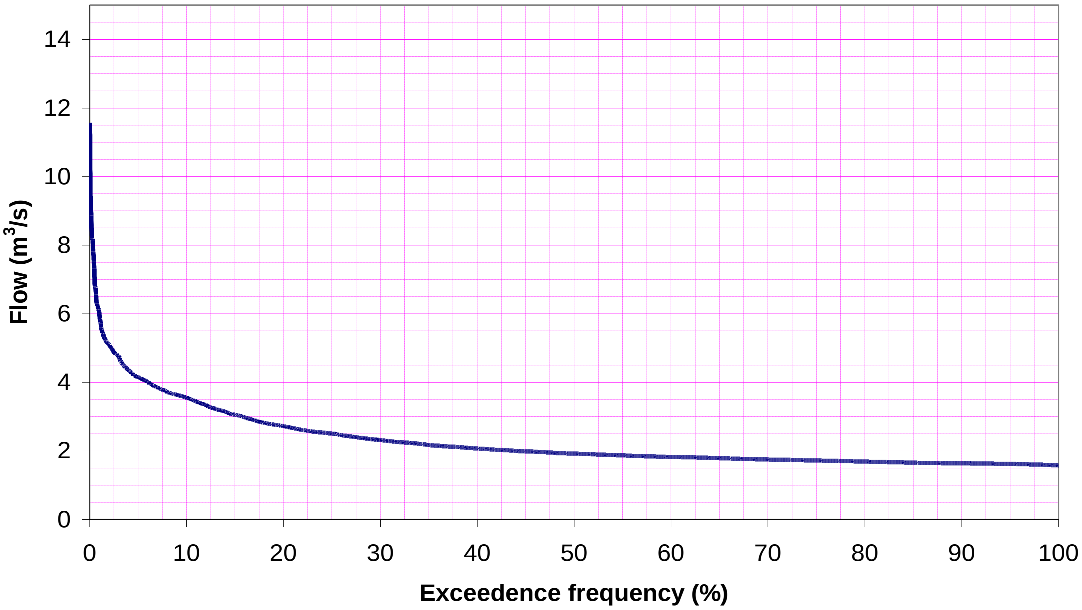
$$Power = \eta \times Q_{95\%} \times H \times g \qquad (2)$$

where Q is the discharge, H is the gross head, η is the overall efficiency of system and g is the acceleration due to gravity.

5. Results and Discussion

The simulations indicate that maximum flows obtained was slightly below 12m^3/s and the minimum was slightly above 1.60m^3/s. The maximum values were obtained during period of rainy season (December to April) the minimum during dry period (July to November). The obtained values do not differ with the flow values which were measured on the upstream point of the river and suggest for a natural flow characteristics. The frequency duration curve developed based the simulated flows (Figure 3) suggest that for frequency of 95% the flow is1.62m^3/s. The potential power generation was estimated to be 226.7 kW at efficiency of 89%. It is fair to note that the upstream land use change and climate variability may alter the current natural flows characteristics.

Figure 3
Frequency Duration Curve at the Proposed Site



Conclusion and Recommendations

The demand for energy is constantly increasing due the increase in the population and the associated socioeconomic activities. Other new avenues for generating energy needs to be explored. This study applied a conceptual model to simulate stream flows for the development of the Jangwani mini-hydropower plant in Ruvuma Region Tanzania. The simulations indicate that for an exceedance frequency of 95% the flow obtained is 1.62m^3/s. The potential of generating electric power is 226.7 kW for efficiency of 89%. The study recommends that the future development on the upstream not alter the natural hydrological processes of the catchment. In a situation whereby the natural flow regime has changed, the development of water storage facility for the sustainability of the system is inevitable.

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