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GIS Based Assessment of Hydropower Potential (A Case Study on Gumara River Basin)

Mehari Kebede Ayele*

Woldia University,Department of soil and water Resource management, North Wollo, Woldia and 400, Ethiopia
P.O.BOX:400, Woldia, Ethiopia
Email: Kmuaz74@gmail.com

Abstract

Energy crisis has emerged as a serious issue all over the world in recent years. Ethiopia is facing a similar crisis that has resulted in frequent power failures and load shedding throughout the country for past several years. The utilization of renewable energy resources may help reducing fossil fuel dependency of the country for power generation. There are various renewable energy options for Ethiopia including solar, wind and hydropower. The objective of this study is to assess the run-of-river hydropower potential of Gumara River using geospatial data and techniques. Gumara River is a tributary Of Abay River located in the Amhara (South Gonder) province of Ethiopia. Satellite data used in this study include ASTER Digital Elevation Model (DEM). Flow data are acquired from regional hydrologic gauges. Geographical Information Systems tools are used for processing the satellite images, delineation of watershed and stream network, and identification of potential sites for hydropower projects.20 suitable hydropower potential Sites were selected. This study will aid decision-makers in the energy sector to optimize the available resources in selecting the suitable sites for small hydropower plants with high power potential. The proposed approach can further be utilized to assess an overall hydropower potential of the country.

Keywords: GIS; Hydropower; Remote Sensing; Renewable Energy; Run-of-River hydropower plant.

1. Introduction

The socio-economic development and increased living standards with the fast growing industry has led to a major increase in electricity demand and generation.

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* Corresponding author.

As a result of rapid increase in energy consumption and global warming threatening the environment together with the unbalanced and unpredictable increases of the fossil fuel prices has increased the importance of renewable energy sources. The main prerequisite for socio-economic development in an area is the acquisition of economic and reliable energy. According to statistics from the United Nations, a total installed capacity of 85 GW should be newly added in the world's rural areas so that the unelectrified rural areas inhabited by ***1.7*** billion people will have electricity for basic needs. However, due to the limitations of conventional energy resources and a shortage of funds and expertise, etc only a few million of rural people in the world can be energized in a year. Therefore the lack of electricity becomes a great constraint to the rural and even the national economic development of a country[1]. Ethiopia is one of the few countries in Africa with the potential to produce hydro power, and estimates of this capacity around 45,000 MW [2]. According to Ministry of water Irrigation and Electricity Development (2017) the existing Hydropower plant installed capacity (MW) to the National Grid of Ethiopia is 3810MW. The main principle of hydropower is to utilize the energy stored in the flowing water when it falls from a height. Flowing water carries enormous amount of energy and when it runs through a steep gradient the amount of energy exponentially increases. There are various sizes of hydropower plants ranging from very large with big dams to small run-of-river projects. The small hydropower projects need low initial investments, smaller area, shorter planning and construction time, locally trained manpower, indigenous material, and lower power generation cost as compared to larger power projects[3]. Hydropower plants are of three types[4].

- Impoundment: this is a large hydropower system which uses a dam to store river water in reservoir. Water stored in the reservoir is then used to generate electricity.
- Diversion: a diversion facility channels a portion of a river through a canal or penstock. This system may not require the use of a dam.
- Run-of-river: the system uses water within the natural flow range and it requires little or no impoundment.

This study presents a prototype cost effective model for assessment of run-of-river (ROR) hydropower potential and identification of suitable project sites using geospatial data and techniques. Ethiopia is in abundance of both water resources in the form of perennial streams and steep slopes. When harvested and utilized properly, the energy produced can help meet the local demand and to raise the quality of life and living standards of the nation. Gumara River is a small river with moderate gradient; it is quite suitable for high head projects. The proposed approach evaluated the hydropower potential of Gumara River as a case study. The ultimate goal of this study was to develop a blueprint that can be used to assess the hydropower potential of the country.

2. Materials and Method

2.1. Description of the study area

The Gumara River is located to the east direction of Lake Tana; it is found between latitude of 11^{0} 35' and 11^{0} 55' N and longitude of 37^{0} 40' and 38^{0} 10' E. Gumera River is one of the tributary rivers of Abay basin which flows into Lake Tana. The river flows westwards for a length of 132.5 km until it reaches Lake Tana. And it has a total drainage area of 127186 ha (1271.86km^2) up to the gauging station. Figure 1 shows the study area. Administratively, the catchment is shared by four woredas (33.69% in Fogera, 31.12% in Farta, 15.56 % in Misrak Estie and 19.63% in Dera). The area has a steep slope (greater than 25%) in the high mountainous region in the east which rises above 2000 m *asl* elevation, and of lower slope (below 3%) towards Lake Tana, the area that ranges from 1700 - 1900 m *asl* altitude. The annual Rainfall is relatively higher in the watershed ranging between 1145

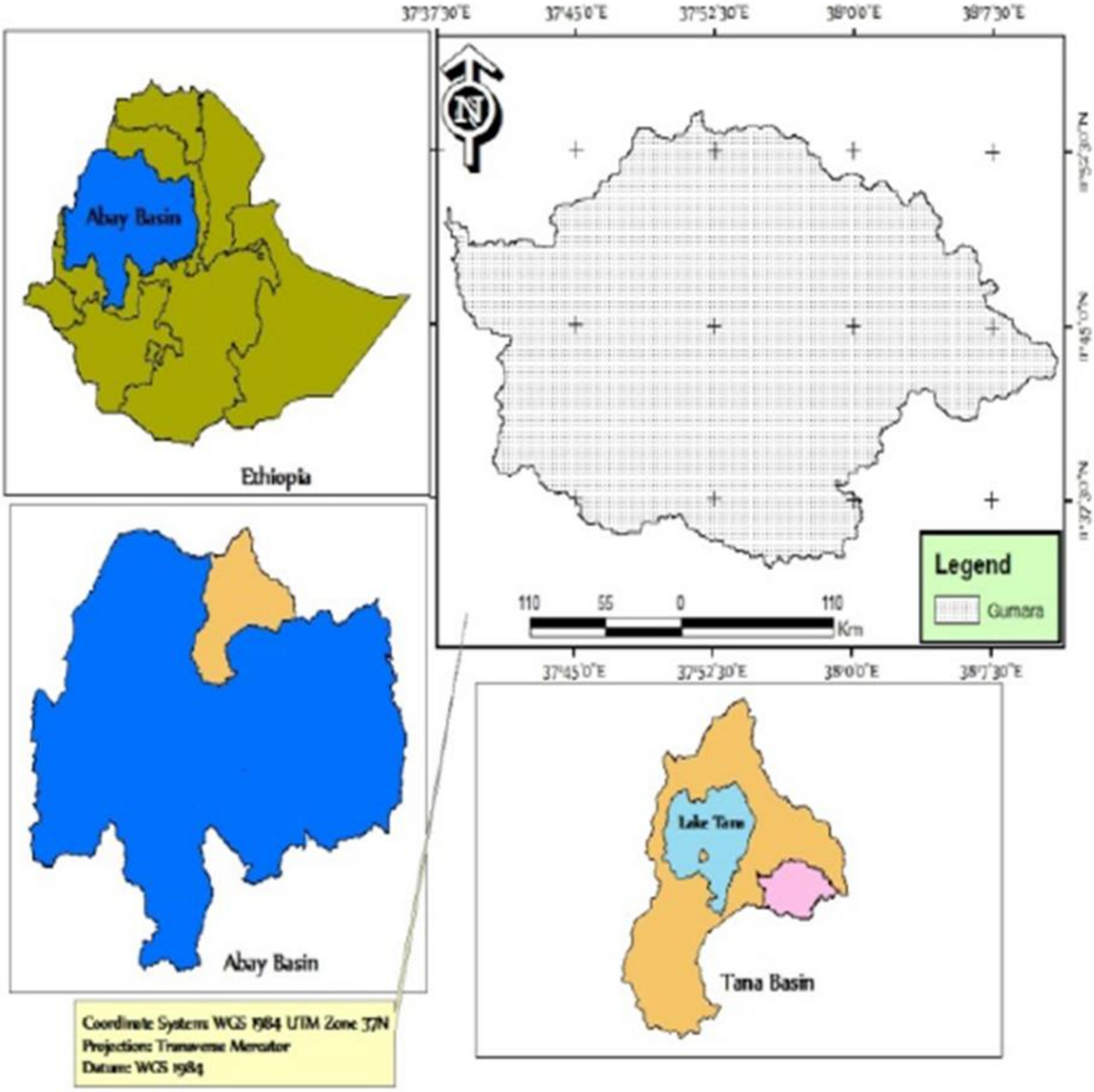


Figure 1: Study Area - Gumara Riv

2.2. Collection and preparation of data

Rainfall Data of 13 point rain gauge stations surrounding the Gumara watershed were collected for a period of

14 year (2003-2016) from metrological station of Bahir Dar branch. And 40year (1970-2009) stream flow data of Gumara River was collected from Abay Basin Authority of Bahir Dar branch. ArcGIS 10.2 and Google Earth tool was used for the data preparation and analysis.

2.3. Method

Run-of-river hydroelectric plants manipulate flow of water and elevation drop (i.e. head) of streams to generate power. This projects are built using a small diversion dam called 'intake' that conveys water from the main water channel to a pipeline or penstock or to generate power on the natural stream course. The penstock further directs the flow to a powerhouse with a turbine[5]. The power potential of flowing water is a function of the discharge (Q), the specific weight of water and the difference in head (H) between intake point and turbine. The mathematical expression for hydropower potential can be written as Equation (1) [6]. In Equation (1), the two parameters, Q and H, need to be calculated. If Q and H are known for a given segment of a stream, the hydropower potential can easily be estimated for that segment.

$$P_{in\text{-}stream} = \Upsilon * Q * H \quad (1)$$

Where, **P** = power potential in kW

Q = stream discharge in m^3/s H = net head in m

Υ= Specific weight of water (N/m3)

Methodological framework of the study is shown in Figure 2. A widely used Geographical Information System (Abate and his colleagues) software ArcGIS 10.2 was used for the processing of satellite derived Digital Elevation Model (DEM).Gumara River watershed and stream network were delineated using ArcGIS extension Arc Hydro. Other ArcGIS tools, Editor and Spatial Analyst, were used to mark proposed sites and calculate their elevations respectively. Discharge analysis was aimed at plotting flow duration curve (FDC) and calculating30, 40, and 50 percentile discharges (Q40, Q50 and Q60 respectively) to fix the size of hydropower plant and firm discharge (Q90) to determine dependable plant capacity using historical flow data. The flow data from one available hydrometric station in the Gumara River were further manipulated to determine the flow at ungauged sites by using Drainage Area Ratio method and Regionalization of monthly flow characteristics using GIS and Spatial Interpolation Algorithm. Finally the outcomes of the above process were fed into Equation (1) to calculate the hydropower potential at proposed sites.

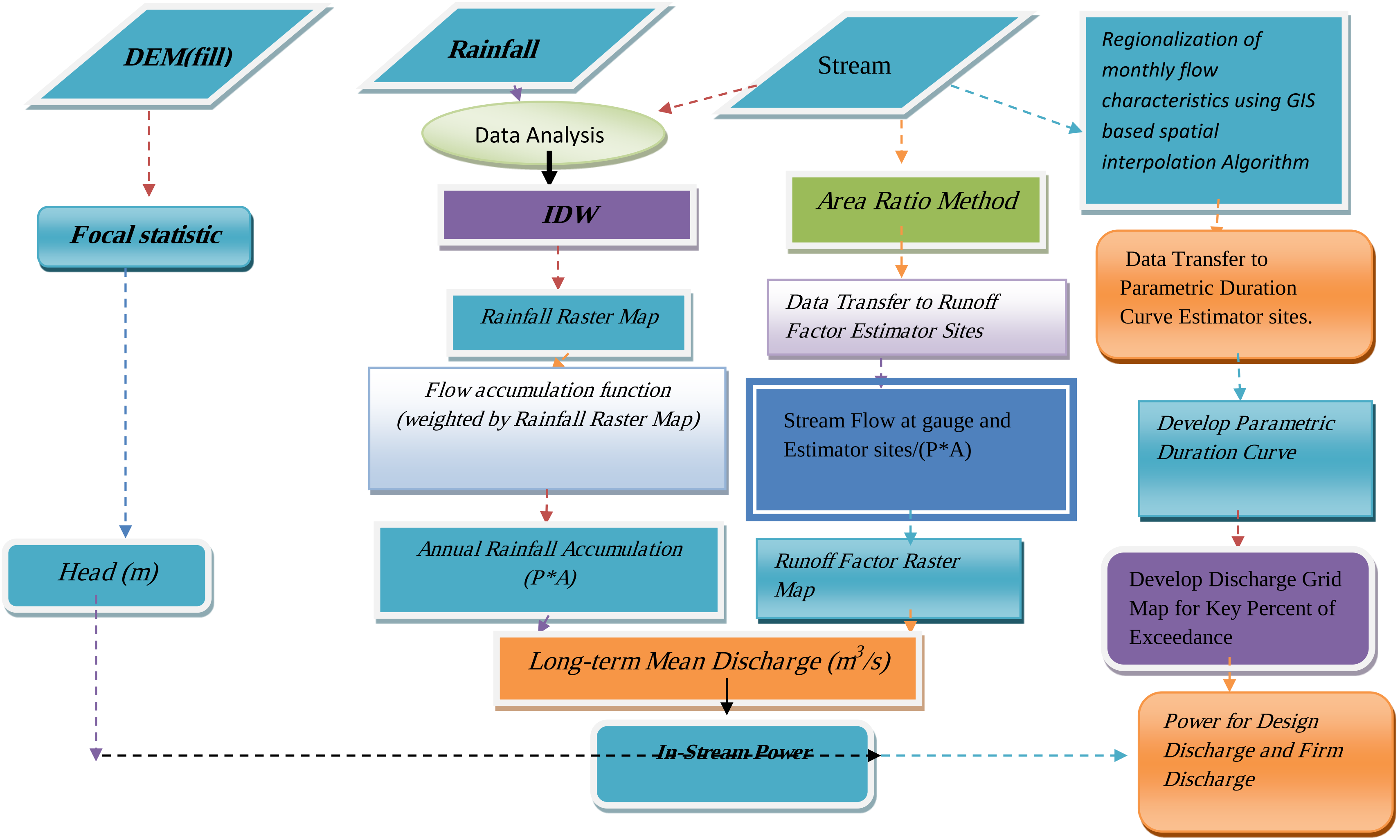


Figure 2: Conceptual Frame work

2.4. Drainage Analysis

Watershed delineation is the first step in doing any kind of hydrologic modeling to determine the basic characteristics of a hydrologic data. Traditional methods used topographic maps for this purpose but in recent years the availability of DEM and GIS tool has made the process simpler and automated. ASTER DEM data of the study area were collected from Abay Basin Authority from Bahir Dar Branch. This DEM had a 30 meter spatial resolution. In this study, Arc Hydro tools were used to process 30 meter DEM to extract drainage patterns of Gumara River basin. The same tools can be used to derive catchment and drainage lines from a selected point to calculate flow at the ungauged proposed sites.

2.5. Head Determination

Head is a vertical distance between two point (intake and turbine). It can also be defined as the pressure created by elevation difference between intake and turbine. Focal statistics function is applied on the digital elevation data. This is a function which computes the necessary statistics (i.e. minimum, maximum, sum of all values) for the neighboring cells surrounding each individual cell. A run-off-river plant does not require space for water storage and 500 meter horizontal distance between two plants is usually considered feasible[5]**.** In the contemporary analysis, the minimum function is applied to a rectangle containing 17*17 cells around each cell which are used to find the minimum cells around each raster cell (lowest neighboring cells).The minimum neighbors' dataset is then subtracted from DEM (without sink), which is 30m*30m resolution, in order to find out the drop elevation of each cell to its minimum neighbors. The output is the height value "head", which is then, used in the equation to calculate the potential energy. The head difference between the DEM without sink and the DEM, which contain a pixel value of minimum elevation of neighboring particular cell within 500m increment, was considered in this study. The head drop obtained for each hydropower potential sites through the method of focal statistics was checked by taking the head of Sample suitable potential sites from the Gumara Watershed by using hand GPS and make its coefficient of determination and Nash-Sutchliff.

2.6. Discharge Analysis

Stream flow data for hydropower potential sites was transferred through the area ratio method for those sites suitable for the requirement of drainage area ratio method. This method is the most appropriate for use when the ungauged site lies on the same stream as a gauging station and the accuracy depends on the closeness of two sites (gauged and ungauged), similarities in drainage area, and other physical and climatic characteristics of the basin[7]. Flow values are transferred from a gauged site, either upstream or downstream to the UN gauged site[8].

$$\mathbf{Q_{ungauge=Q_{gauge}}} * \left(\frac{\mathbf{A_{ungauge}}}{\mathbf{A_{gauge}}}\right)^{\mathbf{n}} \qquad (\mathbf{2})$$

Where: $Q_{ungauge} \sim$ Discharge at the Site of Interest

Q_{gauge}~ Discharge at the gauge site

$A_{Ungauge}$ ~Drainage area at the site of interest

A_{gauge} ~ Drainage area at the gauging site

n~Varies between 0.6 – 1.2

2.7. Predict Average Flow at UN Gauged Points on Streams

Predict average flows at ungauged points on Gumara river basin. The technique called for the development of grid based maps of elevations, runoff factor map and average annual rainfall and then applying various GIS Watershed functions available in the computer program **Arc Map**. The end product was a grid based map of average annual flow in the streams.

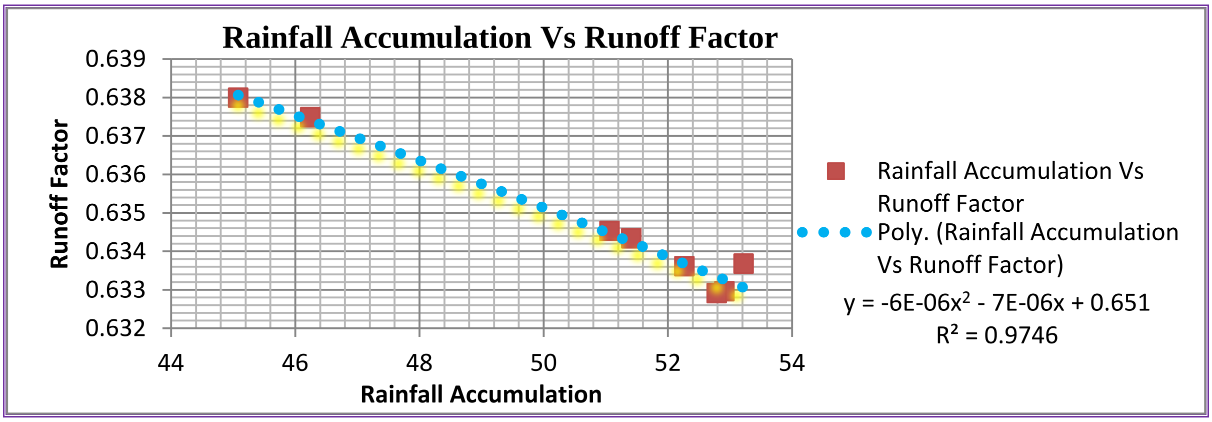


Figure 3: Rainfall Accumulation Vs Runoff Factor.

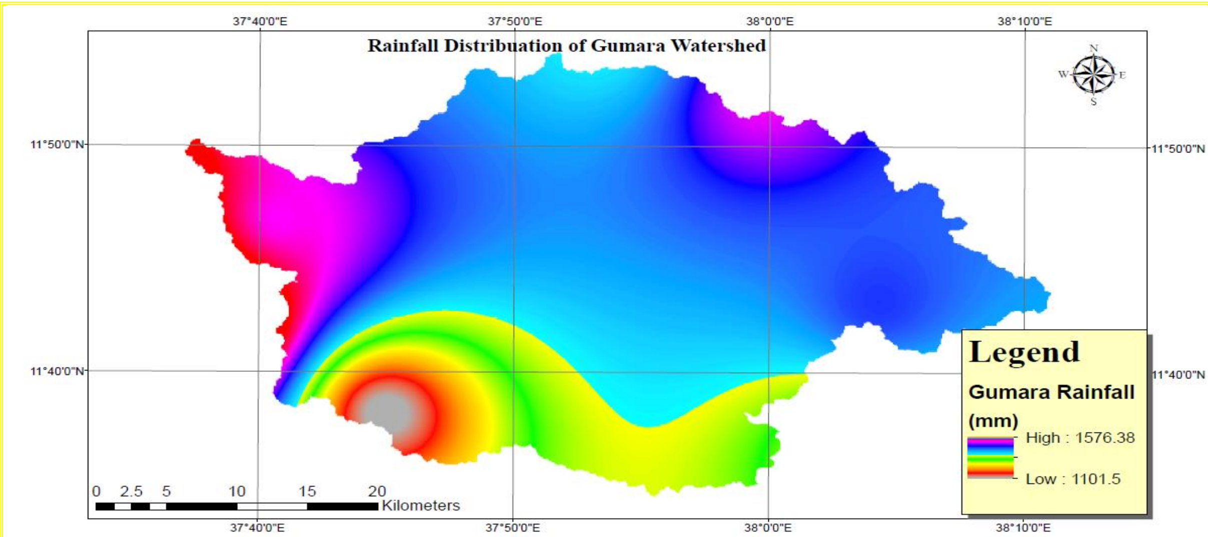


Figure 4: Rainfall Raster Map of Gumara Watershed

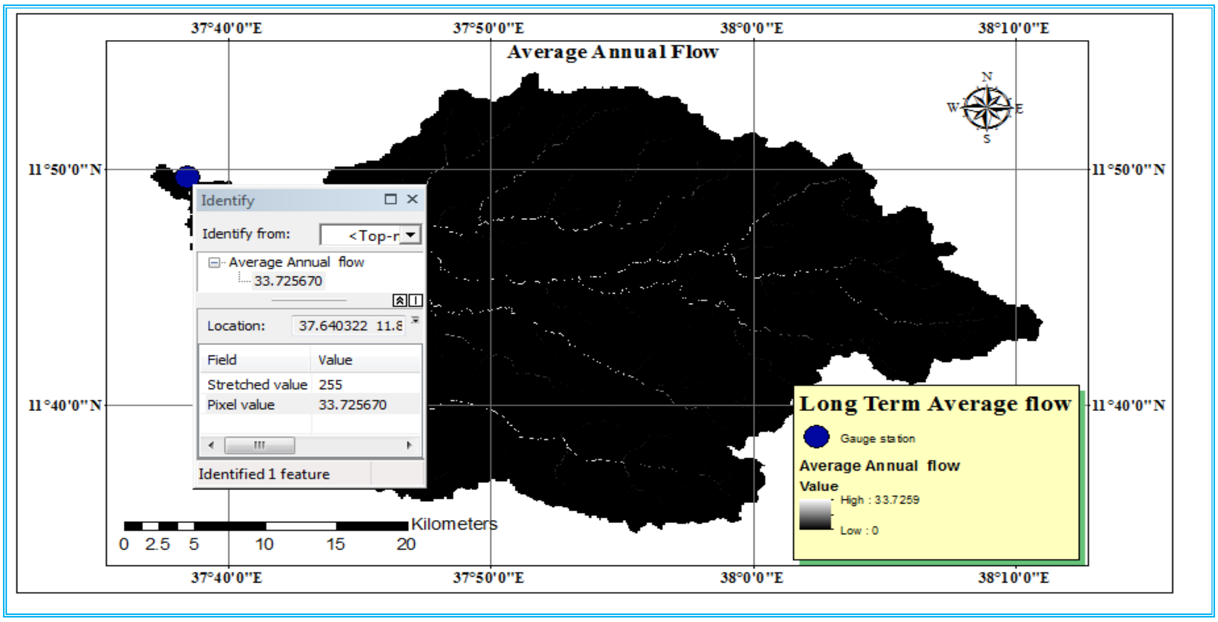


Figure 5: Average Flow Grid near the area of Gumara river gauge station

2.8. Runoff Factor Estimator sites

The runoff factor estimator sites are used to develop runoff coefficient for Gumara flood plain. The drainage area ratio between the gauged site and the estimated sites for Runoff Factor are 1.015, 1.017, 1.026, 1.042, 1.049, 1.15, and 1.18 respectively from the downstream to upstream in the Gumara watershed. The difference of drainage area of runoff factor estimator sites were within 20%of the hydrometric Stations. Most of these sites found at the downstream side of Gumara watershed in order to detect the effect of whole watershed Runoff Formation factors upstream of estimator points.

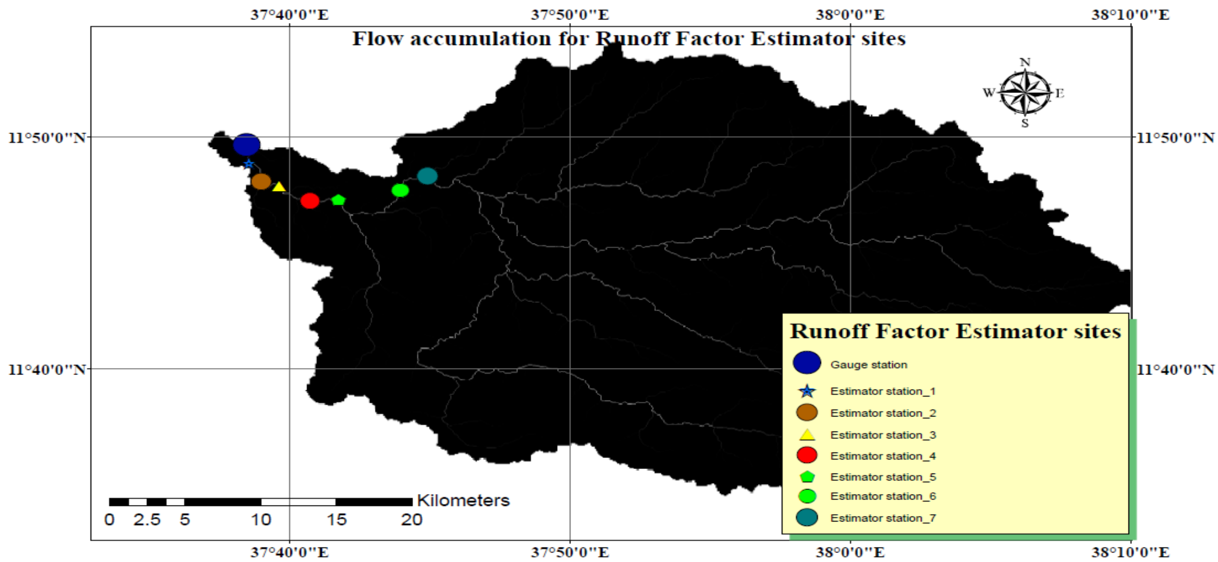


Figure 6: Runoff Factor estimator sites and Rainfall Accumulation grid

2.9. Development of parametric duration curve for key percent of Exceedance

The first step in applying the method was to take the flow values for the key exceedance percentages of Q_{95}, Q_{30}, Q_{40}, Q_{50}, and consider Q_{30}, Q_{40} and Q_{50} from each of the duration curves developed for the gauged station and the corresponding parametric duration curve estimator sites. These exceedance values were chosen because these percentages are important in the sizing of hydropower plants. The long-term average monthly flow was computed for each site. The values of Q Vs long-term Average monthly Flow were plotted for each exceedance value at each site and a best fit curve, which is linear trend line, was matched to the data set recorded in Gumara River Basin. To develop parametric duration curve for Gumara Watershed for the corresponding Key percent of exceedance, which is used for sizing of the hydropower plant, estimator sites should be required. This estimator sites must be selected based on discharge grid value distribution throughout the longitudinal river reach in order to develop representative parametric duration curve. In this study seven (7) representative sites selected from different discharge ranging scale (for instance one cell (pixel value of cell) was selected which represent the discharge pixel value from 10-20m^3/s). Most of the parametric duration curve estimator sites extremely far away from the gauge station. Due to this reason their drainage area size, main stream line slope, topographical condition differ in some extent to that of the drainage area of gauging station. So that, stream flow transfer from gauge site to those parametric duration curve estimator sites, which is deviate from the requirement of drainage area ratio method was done by Regionalization of monthly flow characteristics using GIS and Spatial Interpolation Algorithm. According to [9] regionalization technique, multiple linear regression, flow duration curve, and spatial interpolation algorithm is used for computing daily and Monthly flow time series at un gauged site. GIS is used for computation of the parameter values of multiple linear regressions. The long-term mean daily and monthly flow value can be computed as following [10];

$$\mathbf{\ln Q_{mean} = -\alpha + \beta \ln A + \gamma \ln MAP} \quad (3)$$

Where, Q_{mean} is long-term mean daily or monthly flow (cfs), A is drainage area (sqmi), MAP is Mean Annual

Precipitation

(*in*).Spatial Interpolation Algorithm [9] is developed to generate the flow time series that are timely coincident with the source site. The relationship between the time excess probability values and discharge values of each source site and destination site are like following:

$$\mathbf{Ln(y) = \ln (y_{i-1}) + \frac{\ln(Yi)-\ln(Yi-1)}{Xi-Xi-1} * (x-x_{i-1})} \quad (4)$$

$$\mathbf{Y' = \exp (\ln (y_{i-1'}) + \frac{\ln(Yi')-\ln(Yi-1')}{Xi'-Xi-1'} * (x-x_{i-1'})} \quad (5)$$

Where *x* is time excess probability corresponding to *y* (discharge at FDC of source site)

Y is the discharge of source site (gauging station)

Y' is discharge of destination site (estimator sites)

Xi is 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9, 99.99 % value of time excess probability (I=1~17).

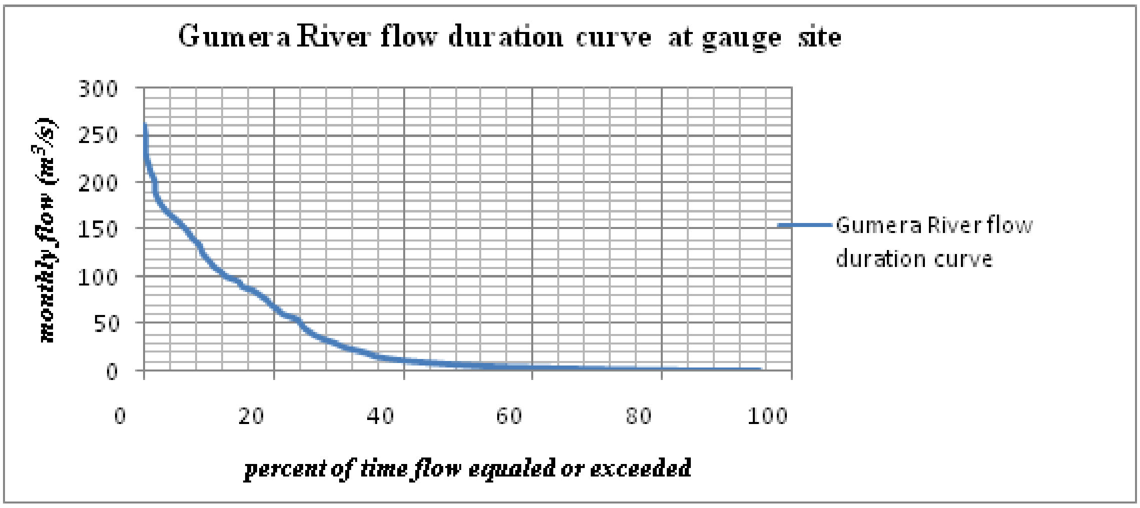


Figure7: Flow duration curve for Gumera River at gauge station

The key percent of exceedance of gauge station with the corresponding quintile of discharge computed by spatial interpolation algorithm was shown below.

Table 1: Key percent of Exceedance with the corresponding discharge quintile

key percent of exceedance	Magnitude of discharge (m^3/s)
Q(0)	**260**
Q(10)	**116.64**
Q(30)	**28.02**
Q(40)	**11.66**
Q(50)	**6.33**
Q(80)	**1.34**
Q(90)	**0.71**

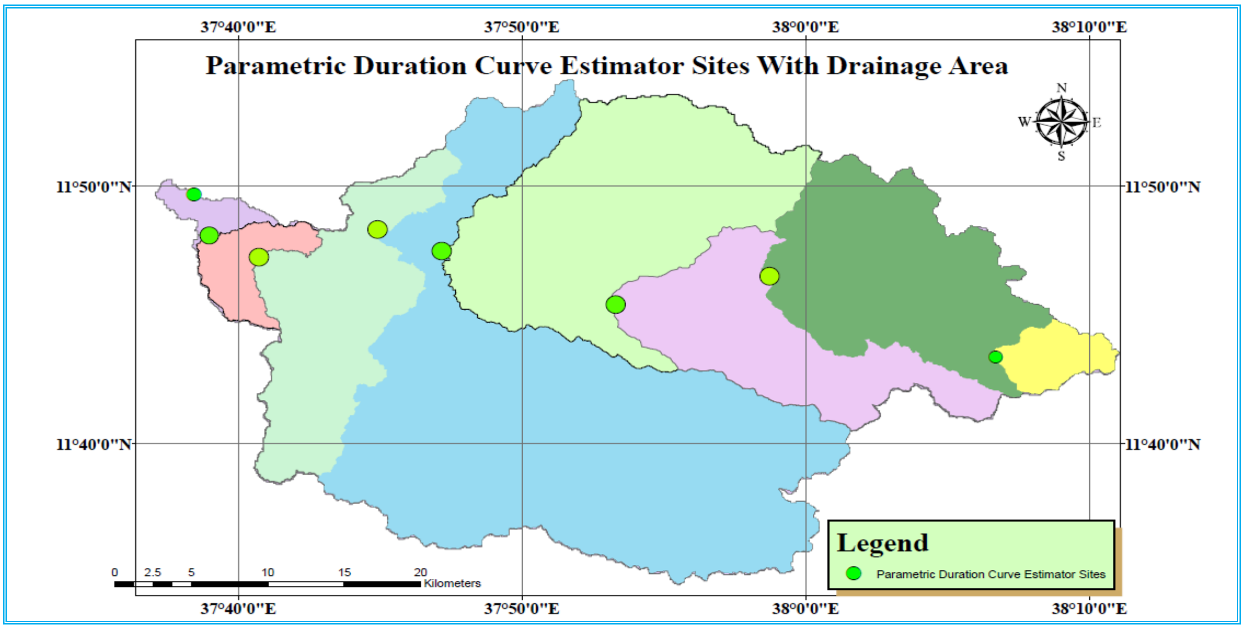
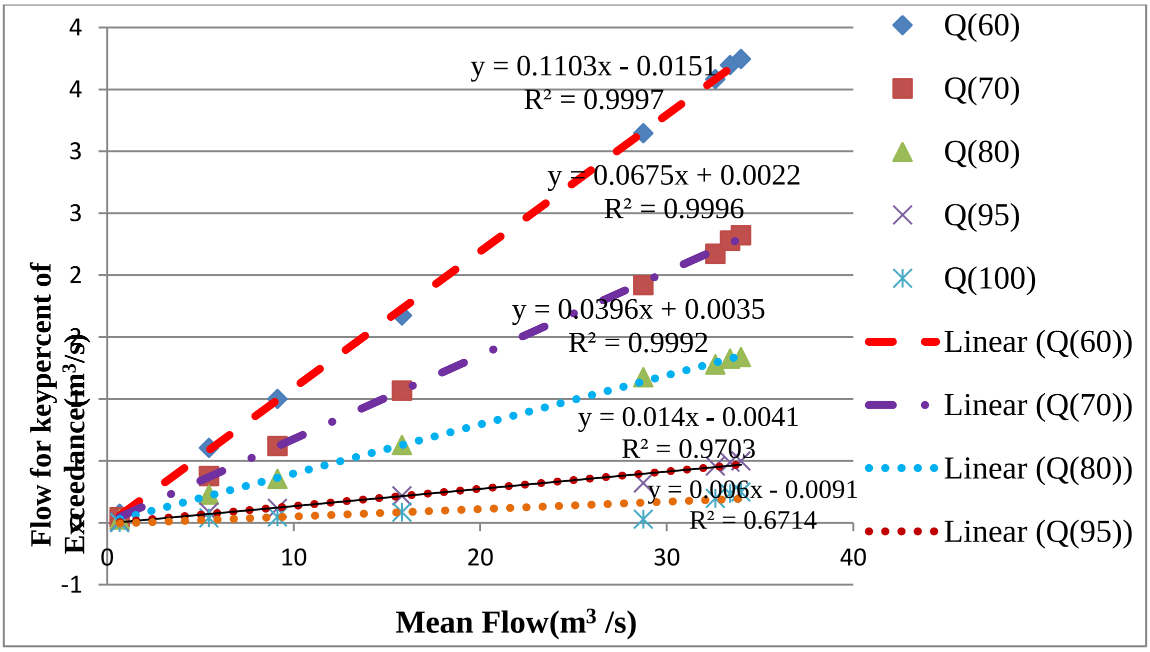


Figure 8: Parametric Duration Curve Estimator sites.



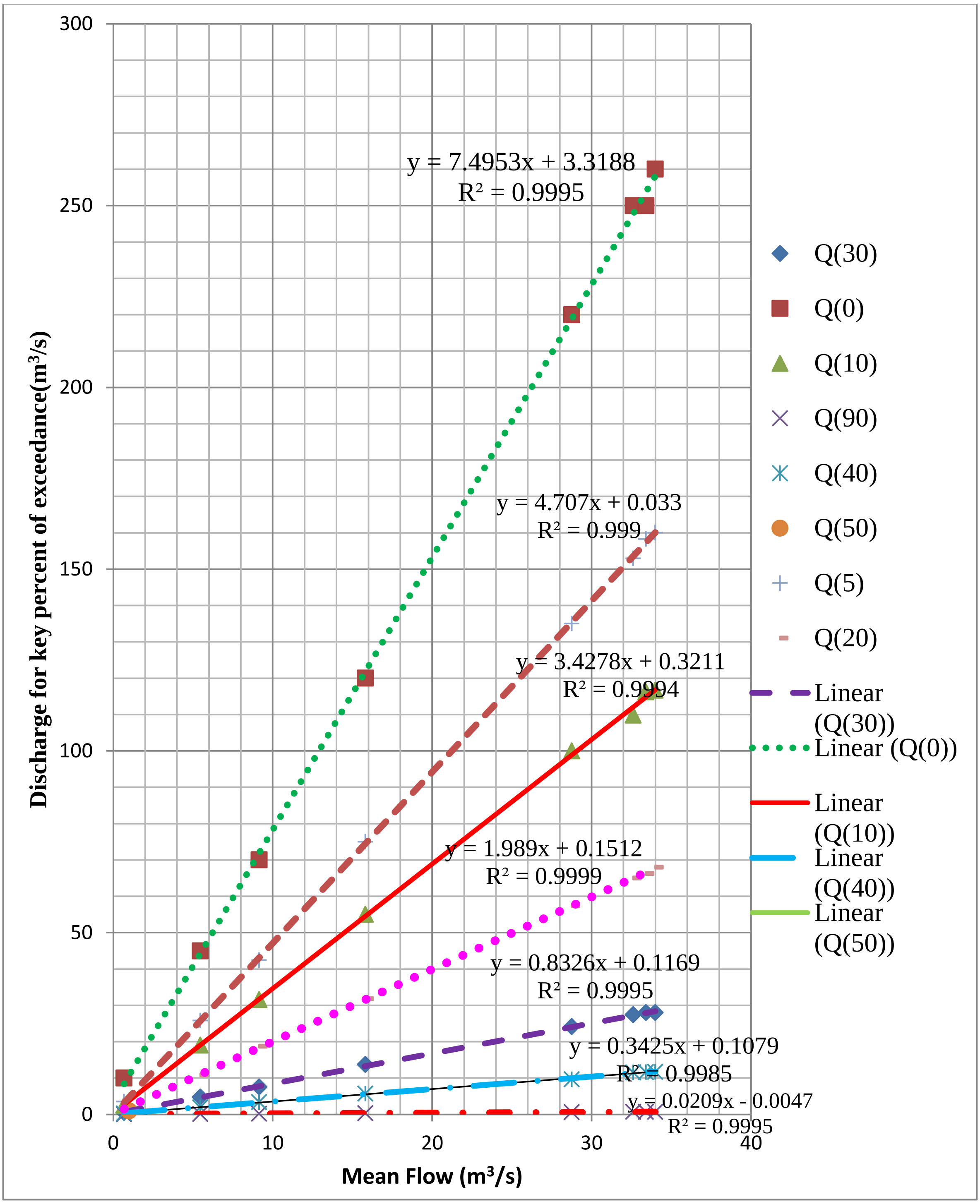


Figure 9: Parametric duration curve of Gumara watershed

2.10. Identification of Suitable Sites for Hydropower Plant Based On Sensitive Criteria

To select hydropower feasible sites, selection criteria should be developed. In this study In-stream power, Discharge and Head was considered as selection criteria. The table shown below describes sensitive criteria with the corresponding range of criteria's.

Table 2: *The criteria and limits to identify potentially feasible sites*

Parameter	Valid Range
Long term dependable annual Discharge	>=0.1m^3/s
Head	>=5m
In Stream Power	>30kw

By using fuzzy overlay analysis of raster map of those criteria, which intersect or inclusive the above three criteria should be selected in the GIS Environment.

2.10. Prioritization and Suitability Analysis of the Hydropower Sites Based On GIS Based Multi Criteria Analysis(GIS-Mca)

GIS-based Multi Criteria Evaluation (GIS-MCA) can be defined as a process that integrates and transforms geographic data (map criteria) and value judgments (decision maker's preferences) to obtain overall assessment of the decision alternatives[11]. In this study Selection of Suitable sites for hydropower based on the given criteria were done by GIS based Multi criteria analysis (GIS-MCA).

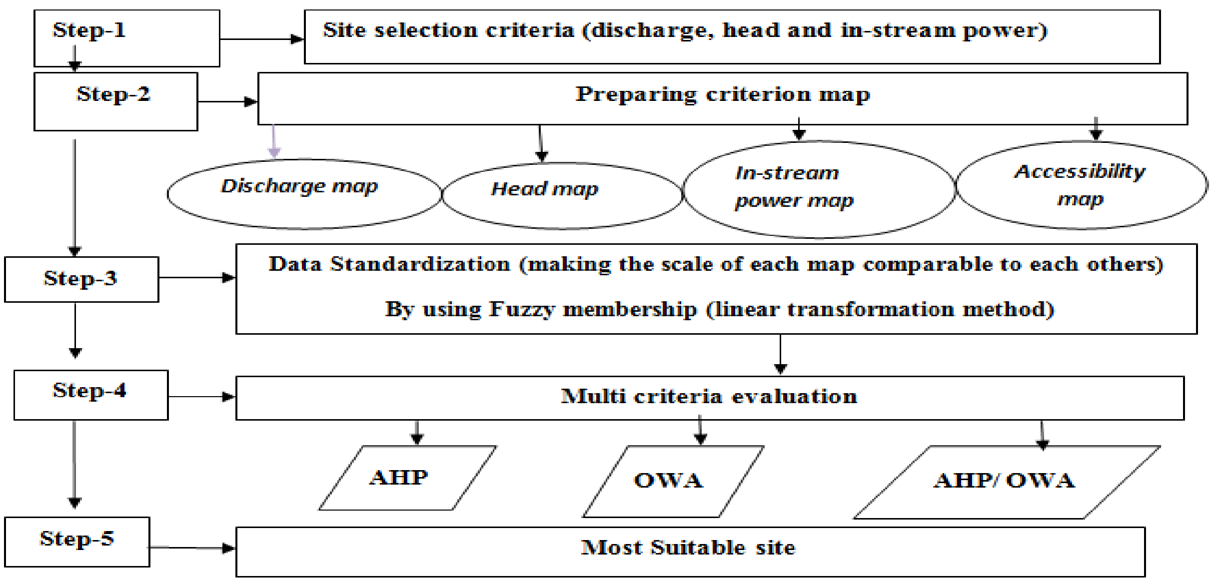


Figure 10: Procedure for most suitable site selection

3. Results

3.1. Identification of Suitable Sites for Hydropower Plant Based On Sensitive Criteria

The sites which are suitable for hydropower potential Development throughout the streams within the Gumara Watershed were analyzed and suitable sites were selected based on Raster based value of In-stream power, Head and Discharge, which a the principal factor for Hydropower evaluation. **20** suitable sites were selected based on the criteria.

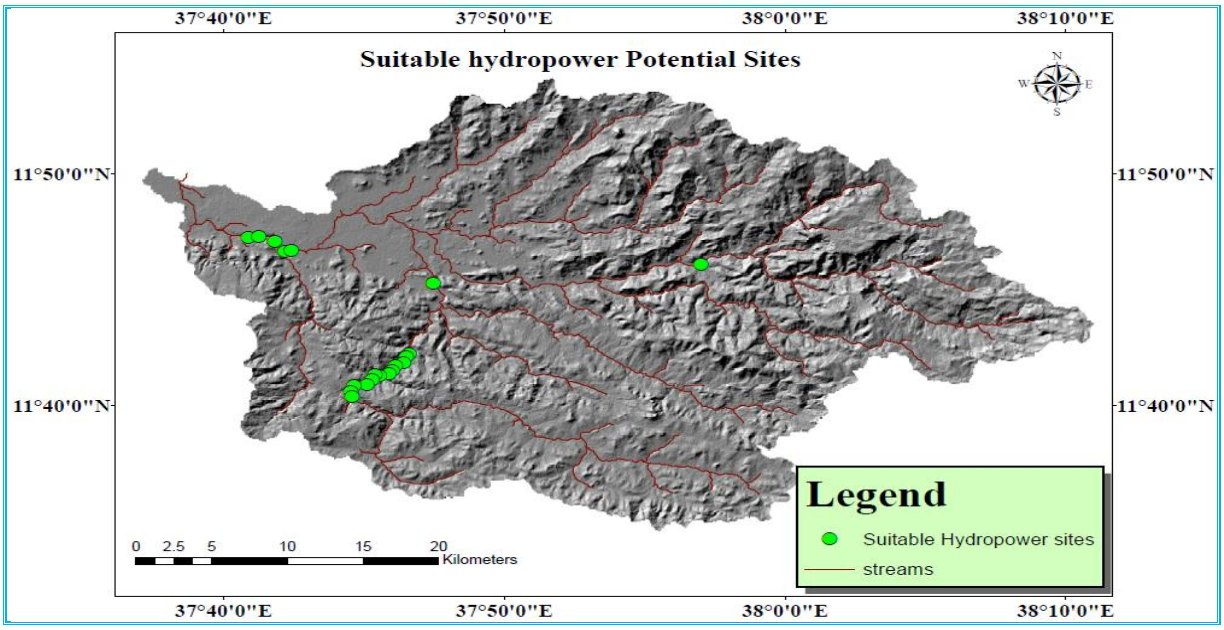


Figure 11: Suitable Sites for micro to Small scale hydropower potential in Gumara Watershed.

3.2. Theoretical power potential of Gumara river basin

There were two important parameters that can define the hydropower potential of a location along a stream. These parameters are elevation difference between upstream and downstream points which is also called head and discharge. Total potential (in Watts) of Gumara River, assuming 500 meter as an optimal interval between the proposed plants, is calculated for each percentile discharges i.e. Q30, Q40,Q50 and Q90. For this study, heads are calculated at 500 intervals along the river using DEM and the corresponding discharges at these locations are estimated.

Table 3: Power for $Q_{30,}$ Q_{40} and Q_{50} *(in Kw)*

	P_{30}	**P_{40}**	**P_{50}**	**P_{90}**
Total Theoretical hydropower potential	**18217.899**	**7596.841**	**3985.037**	**425.544**

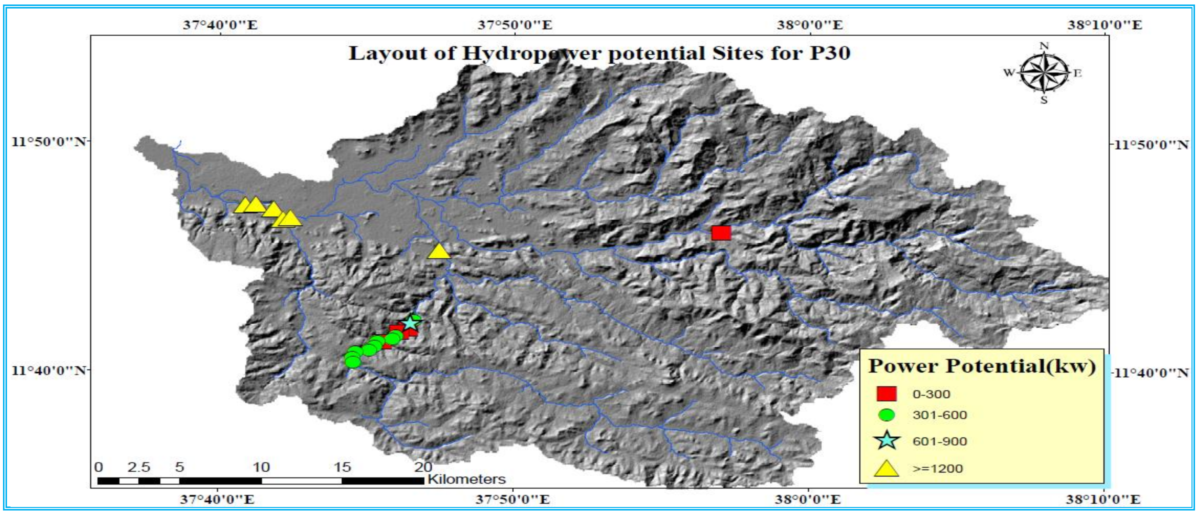


Figure 12: Spatial distribution of suitable sites for ranges of hydropower potentials.

3.3. Technical Power and Energy Output for Gumara River Basin

Technically available power is obtained by including losses due to conveyance, plant losses such as entrance loss, rack loss, generator and turbine loss etc. The technical (Real) power equation for small scale hydro power is between P = 7QH and P= 8.5QH (Lee and his colleagues) [12]. To find the annual energy the formula presented below is used.

$$E=\Sigma P\ \Delta T_i * Y \quad (6)$$

Where **E**=average annual electricity production, **GWh**

ΔT = increment along the percent scale (10% and 5%)

Y - Is the number of hours in a year i.e. 8760 hr.

The total annual energy output of all sites as calculated using FDC (flow Duration Curve) method of flow duration curve is found to be **105.89GWh/year**.

3.4. Prioritization And Suitability Analysis Of The Hydropower Sites Based On GIS Based Multi Criteria Analysis (GIS- Mca)

Prioritization of suitable hydropower potential sites of Gumara river basin was performed based on the Grid based Raster map of In-stream power, Discharge, head and Accessibility of Gumara watershed. The output for standardization of raster maps of in-stream power, discharge, Head and accessibility of Gumara watershed have been done.

3.5. Criterion Weights

In this analysis, factors selected to evaluate the hydropower potential sites, were standardized using the pair wise comparison method. In this process, each factor is rated for its importance relative to every other factor using a 9-point reciprocal scale. This leads to an n x n matrix of rating where n is the number of factors being considered[13]. Out of the four criterion for prioritization analysis greater weight was given for In-stream power, which is 46.1% followed by Discharge(29.2%).the third factor is Head, which has a weight of 18.5%.the last one is accessibility, which has a weight of 6.5%.

3.6. Creating Final Map Using Weighted Linear Combination Method

In this study, WLC model is implemented within the GIS environment using map algebra operations. To complete the analysis, the raster calculator was used to find the ideal locations for hydropower development. Therefore, four criterion maps were integrated by applying weights as criterion weights:

[In-stream power]* 0.461 + [Discharge] *0.292+ [Head]* 0.182 + [Accessibility (road proximity)]* 0.065

The result of this integration shows potential sites (ranked from best to worst) that could be suitable for hydropower development.

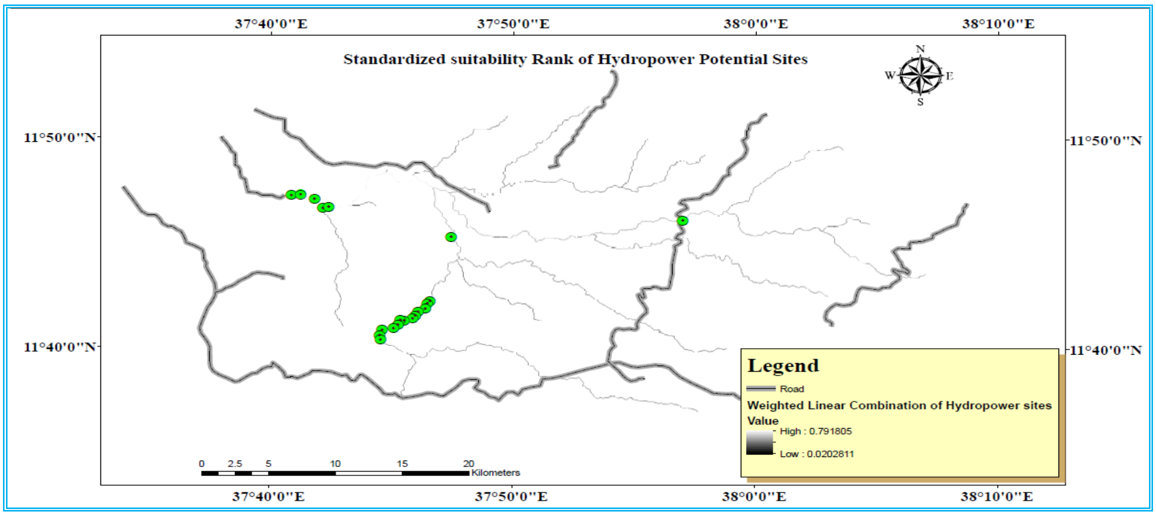


Figure 13: Suitability of Hydropower potential sites Using WLC Method.

4. Conclusions

The recent energy crises in the country and overexploitation of non-renewable energy sources have created a gap between supply and demand of this vital commodity. Unsaved communities living in small settlements far from the main energy grid stations are the main sufferers of this situation. This study is an effort to establish the importance of renewable energy sources and to present a methodology to investigate the feasibility of installing small plants at locations which have adequate hydropower potential. The theoretical and technical Run-of-River Hydropower potential was estimated based on different algorithm and feasible hydropower potential sites was identified based on Multi Criteria Analysis on the Gumara Watershed. Accordingly the estimated total theoretical ROR hydro potential of Gumara River basin is 18217.899 Kw, 7596.841Kw, 3985.037 Kw and 425.544Kw for 30%,40%, 50% and 90% flow exceedance respectively and the total Energy output of **105.89GWh/year** was obtained for selected hydropower potential Sites. The finding of this research provides valuable insights. The estimated theoretical hydro potential in this study has provided the new potential figure for the major rivers of Gumara. This will provide the fundamental information to the government and concerned stakeholders to formulate plans and policies to develop hydropower in the country

5. Recommendations

This study has highlighted the need for the developing country like Ethiopia as a whole to adopt rural electrification as a key policy of government as it improves the living standards of the people and reduce poverty by the creation of new income sources in rural areas. It is clear that the utilization of small-scale hydropower can provide a viable source of energy to increase the electrification levels in Ethiopia. Exploring the potential of SHP scheme as eco-friendly source of energy serves the least cost option for provision of electricity to underdeveloped rural areas compared to the extension of grid. They are affordable if necessary subsidy is provided. Furthermore, the value added benefits of the scheme is as follow: Availability of local labor and materials; thereby, increasing the income of the poor. They help to check rural/urban immigration. They are flexible and can usefully be integrated into almost any kind of development program such as rural development, poverty alleviation program and environment protection programs. However, small-scale hydropower will only be able to fulfill this role if certain policy and other issues are addressed before implementation of projects. As a result, this study has made a number of recommendations, a summary of which is provided below:

- More hydrological data needs to be collected over a period of time. In order to achieve this goal, technical equipment such as a network of gauging stations is required along with human capacity building.
- Build or improve local manufacturing capacity to produce components such as low cost turbines for small hydropower plants.
- Providing clear and agreed environmental compliance standards at licensing.
- With a well arrangement of system of power plant structures, new environmental impacts will not be introduced.

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