Assessment of Hydropower Potential Using Geospatial Technology in a Case Study of Guna-Tana Landscape Upper Abay Basin, Ethiopia

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Research

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Abstract

Background: In this study, geospatial technology was used to assess potential sites for hydroelectric potential in the Ribb and Gumara Rivers of the Guna-Tana landscape of the upper Abay basin in Ethiopia. The important parameters used in this study were the Digital Elevation Model, the stream network, the stream elevation; the stream slope, the height difference, and the stream flow were analysed. In addition, the results obtained from the geospatial model, satellite data and GIS tools were used to identify the hydroelectric potential in the landscape.

Results: Twenty sites with hydroelectric potential were identified within the 3528.16 km^2 of the Guna-Tana landscape. The maximum power in the Ribb River was 48,389.98 kW, while in the Gumara River it was 41,984.01 kW. Therefore, the development of strategies to improve the decision-making process for hydroelectric power planning and construction is of utmost importance to support renewable energy production with minimal negative environmental social impacts.

Conclusion: Therefore, this study revealed that the hydroelectric potential of a river basin could be correctly assessed using a digital elevation model, stream network data, within a GIS framework.

Introduction

The whole world is in the grip of the energy crisis and pollution manifests itself in the rising cost of energy and feels uncomfortable due to increased pollution, as well as the depletion of conventional energy resources and the increasing curve of the elements (Edeh, J., 2016). It is commonly accepted that the standard of living increases with the increase in per capita energy consumption (Arto, I., 2016). Any consideration of energy needs and supply must take into account increased conservation measures (Turner, K., 2013). Hydropower is a clean, renewable and reliable source of energy that meets the goals of national energy and environmental policies. The energy produced by hydroelectric energy is derived from the basin of the watercourse or stream due to the force of gravity; therefore, the effect of greenhouse gas emissions is less than that of wind energy (Kusre et, al, 2010). The renewable resources and their utilization is still a current topic of social events. Hydropower represents only a certain amount of energy, which has the planet (Ellabban, O., 2014). Water is an irreplaceable natural resource, essential for life. Its movement depends on the environment (Boyden, S. and Dovers, S., 1992). Using the potential of watercourses is currently a hot topic (Whitehead, P.G., 2009). Energy from hydropower can build energy independence on other sources and thus contribute to economic growth mainly of small parts. The aggregate contribution of hydropower has been estimated as 6.15% of the total world energy mix (BEE, 2007).

Hydropower was referred to as a source of energy, which allows generating electricity without using fossil fuels (Surekha and Dudhani, 2006). Hydropower is a renewable and sustainable source of energy for global challenges (Frey and Linke, 2002). Sustainable and qualitative growth for economic and housing development requires increased energy input from renewable sources, while maintaining ecosystem balance during operation (Palani-chamy et al., 1999). Among the renewable energy technologies, small hydropower is one of the most attractive and probably (Hammons, T.J., 2007). Global installed capacity of Small Hydropower today is around 47,000MW against an estimated potential of 180,000MW (Naidu, 1998). Because of this, the study focused on community based assessment of small-scale hydropower potential of Guna-Tana watershed. Hydropower has generated considerable interest because it is a renewable source of energy and is a convenient means of providing electricity to far flung areas in hilly regions. The running costs of hydropower installations are very low compared to thermal or nuclear power stations (Dandekar and Sharma 1979), since the fuel (water) is virtually free. Hydropower projects can be classified in many ways: by size (large, medium, small and mini scale); by purpose (single or multi-purpose). Hydropower is environmentally friendly, cost effective and, unlike oil and other commodities, independent from international trade. Construction of a hydropower project requires proper planning and a detailed survey of the topography and flow availability within the basin (Pandey, A. et al., 2015). Hydropower development in hilly terrain requires a thorough study of the geology, topography, and land use patterns, availability of resources, infrastructure and socio-economic activities (Pokhrel, Y., et al., 2018). The feasibility study and baseline survey for hydropower are very difficult, time consuming and costly. Hilly regions with high annual precipitation have potential for hydropower development, but at the same time there are many problems in accessing the remote areas. Further, construction of dams may also lead to displacement of population and submergence of forests and such projects may face opposition. Correct assessment of hydropower potential at a site requires realistic information on topography (particularly elevation) and flows followed by careful analysis of these data. Recent advances in remote sensing (RS) and Geographic Information System (GIS) provide realistic, up-to-date and useful information for the assessment of hydropower potential. Guna-Tana landscape as the other part of country the energy assessment has been done by different researchers (Mentis, D., et al., 2016), but the study is not detail enough and the assessments done are not updated to the changes due to continuously changing world climate change. The collection and analysis of accurate information on topography, land use pattern, river morphology and geology is easier in the GIS environment than by conventional field survey, as GIS can manage all variables with reference to location, and can provide a clear picture about the hydropower project area and its impact zone (Pathak, M., 2008). Certainly, the combination of GIS and RS techniques provides a powerful tool for the assessment of hydropower potential. Therefore, the aim of the present study was to assess potential hydropower sites by exploring the application of Remote sensing data and GIS in Guna-Tana landscape.

Methodology

Description of the Study Area

Location of study area

Guna-Tana Landscape is located in the South Gondar zone, which is part of the Amhara Regional state covering an area of 3528.16 km² (Fig.1). The coordinate systems of the basin extends from 37° 53' 13.555" E to 11° 53' 17.460" N. The elevation ranges from more than 4090m in the highland to around

1752m in the floodplain. An undulating and rugged topography is dominating the basin containing steep slopes in the mountainous region in the east and more gentle slopes towards Lake Tana.

Methods

Identification of sites and determination of flows at selected sites have been the requirements for assessment of hydropower potential. The methodology used to assess hydropower of Guna-Tana landscape is identified on Gumara and Ribb rivers. The hydraulic head and the availability of flow are the two major components of hydropower generation. The assessment of head, site selection and simulation of flow at each selected site was carried out using the ArcGIS. The ArcGIS tool generates stream network characteristics, the length of the river, and elevation difference for each stream within the watershed boundary. The model has provision for addition or deletion of outlets and inlets by user intervention, which affects the delineation and number of sub-watersheds created by the model, and this facility was utilized in assessing the head variation along the river, by placing sub-basin outlets at different locations.

Data collection

Acquisition of Digital Elevation Model (DEM)

A DEM supplied from Alaska data were used to obtain Elevation difference, slope and other spatial information. The Alaska DEM with a spatial resolution of 12m was freely available and it was downloaded from website Alaska satellite facility's vertex.daac.asf.alaska.edu.   the steps followed to download this DEM was as follow from the website mentioned above downloading single band for study area, then mosaicking each band in ERDAS 2016 software and finally prepared the composed band which give the DEM of study area (figure 2a). DEM is used as the input in ArcGIS software to generate various maps based on different basin characteristics. It is a raster whose grid values signifies the height of the surface. The elevation data (figure 2b) for the study area is obtained from Digital Elevation Model (DEM) is used to find out the head available at different locations.

Slope Map of the study area

Slope calculates the maximum rate of change in value from that cell to its neighbours. The maximum change in elevation over the distance between the cell and its eight adjacent cells identifies the steepest downhill descent from the cell. The slope of the streams were generated from the slope map of the study area to identify the potential hydropower areas on the rivers.

Flow direction map of the study area

The flow direction map represents the direction of flow out of each cell. The input required is the DEM of the study area in the form of raster. The flow direction is based upon eight direction (D-8) flow model (Kinner, D.,. et al., 2005). In this model, there are eight valid output directions relating to the eight neighbouring cells into which flow could travel.

In the figure 4a, we can see a raster of elevation surface. Let us consider the 1st grid whose value is 78. Its adjoining cell have values 72, 67, 74. The minimum value among these is 67. Thus, the maximum slope is in the direction joining the cell 78 and 67 i.e. the southeast direction. Similarly, the value is assigned for every cell of the elevation surface. The resultant raster formed is the flow direction raster. The direction of flow is determined by the direction of steepest descent, or maximum drop, from each cell (figure 4b). The Flow Accumulation tool in ArcGIS software calculates accumulated flow as the accumulated weight of all cells flowing into each downslope cell in the output raster. In a simplified manner, we can say that the flow accumulation value of a cell represents the number of cells accompanying flow to that cell.

Assessment of hydraulic head

To assess potential hydraulic head along the river, computations were started at the main outlet of the watershed and then preceded in the upstream direction (Hundecha, Y. and Bárdossy, A., 2004). A location is identified as a potential hydropower site when a head of 20 m or more is available in a stream and the distance between the current location and the site immediately downstream exceeds 500 m (Kusre et al. 2010). A low head hydropower application uses river current or tidal flows falling through 20 m or less to produce energy. This is to ensure that the tailrace of the upstream site is not influenced by the reservoir of the downstream site. The assessment for the next potential site is carried out from the last selected site and the process continues to the upstream end of the river. In this study, only the potential ROR sites where power could be generated without constructing a reservoir were identified. Run-of-river schemes do not require a dam or storage facility to be constructed; instead, they divert water from the stream or river, channel it into a valley and then into a turbine via a pipeline called a penstock. Such ROR schemes can generate power for use in homes, hospitals, schools and workshops, providing an environmentally friendly way of harnessing energy from the falling water of steep mountain rivers such as Gumara and Ribb Rivers in Guna-Tana landscape. Small hydropower schemes such as these do not cause damage to the environment, can make a sustainable contribution to the electricity crisis and help the economic development of hilly areas. A hydropower plant without pondage has no storage, is, therefore, subject to seasonal river flows, and serves as a peaking power plant, whereas a plant with pondage can regulate water flow and serve as either a peaking plant or base-load power plant. Therefore, it is important to be able to estimate river flow.

Estimation of flow

Many times situation arises when the discharge observations are not available at all for streams and flow assessment has to be made for planning and the preparation of project report of a possible project site (Adhau, S.P.,. et al., 2012). Depending on the availability of data of the sites or basins there are various methods to estimate the discharge of the streams in order to identify potential hydropower sites on the stream. The discharge data was obtained from Amhara metrological station for both Ribb and Gumara rivers. The missing discharge data were filled for final analysis. To first locate the feasible locations based on head, we need to find streams with adequate flow. More is the order of the stream; more probability is there that adequate flow is available. Hence, to ensure the sufficiency of flows only streams with a minimum stream order of 3 is considered. The stream order is based on Stalher's criteria. According to the Strahler method, the stream originated from the top most elevation is marked as first order stream. The uppermost stream are assigned stream order number 1. When two N^{th} order stream meets, the resultant stream becomes $(N+1)^{th}$ order stream. Similarly, when a higher order stream meets the lower order stream, the resultant stream becomes the higher order stream.

Criteria for identification of sites for selection of the potential sites for a hydropower project, the following criteria were adopted:

(i) **Availability of flow**

The availability of adequate flow is to be ensured:

By considering only streams that have flow accumulation of 12000 cells or more, as ascertained from the flow accumulation map; and as two second-order streams join to become a third-order stream, this will have sufficient runoff for installation of a powerhouse; thus the flow accumulation map was examined along with the digitized drainage map to make sure that only streams of third-order or more are considered.

(ii) Site spacing

(a) The minimum distance between two consecutive sites should not be less than 500 m

(Kusre et al. 2010). This will ensure that there is sufficient gap between the tailrace of one site and the diversion arrangement of the next, so that the river ecosystem will have sufficient opportunity to rejuvenate.

This will also ensure that the tailrace of the upstream site is not influenced by the reservoir/pondage of the downstream site.

(b) The maximum distance of river considered to find the head should not be more than 3000 m.

(iii) Head availability

(a) The head availability is assessed starting from the main outlet of the watershed.

(b) A project should have at least 20 m of head. (c) If the 500 m criterion is not satisfied, the

Hydraulic head is repeatedly raised until the interval constraint is meet.

Estimation of hydropower potential

The amount of power generated when a discharge is allowed to fall through a head difference of H is given by:

$$P = \rho g Q H \eta \qquad (1)$$

Where: P is power, ρ is the density of water (1000 kg/m^3

g is the gravity acceleration (9.81 m/s^2) and

η is the overall efficiency of the turbine or generator. The amount of power generated will increase with the increase in Q and H. In this study, the theoretical power is estimated by using the ArcGIS environment.

Units and Power Estimations

Power: watts [W] or Kilowatts [kW] 1 kW = 1000W
Flow: 1 m^3/s = 1000 l/s
Gross heat: height difference the water "falls down"
Net head: a little smaller than gross head. Gross head deducted by energy loss due to friction in penstock.

Potential power ('*electric)'* is calculated as follows:
Power [W] = Net head [m] x Flow [m^3/s] x 9.81 [m/s^2] (est. gravity constant) x (turbine/generator efficiency)
Potential power is estimated as follows:

More estimations that are accurate take into consideration:

- exact net head (intake to powerhouse)
- Exact flow (constant during the year?)
- combined efficiency of turbine and generator (depends on quality)

Criteria for identification of sites

1. Order of stream: Only fifth and higher order streams are considered for selection of sites to ensure sufficient amount of water flow.
2. Bottom gradient: Selected site should be such that average gradient along the bottom of the stream should be 1:50 (i.e. 2%) or more to ensure sufficient potential head.

iii. Minimum hydropower site interval: Distances between two consecutive hydropower sites should not be less than 500 m.

Identification of hydropower sites

To select suitable sites, the Digital Elevation Model (DEM) and stream network were used. The DEM that describes the terrain features of the study watershed was obtained from website as described earlier. The contour data at 20 m interval were extracted from the DEM. DEM, the stream network were overlaid to ascertain the elevation, and hence the available drop along the streambed. Search for the suitable locations initiated from the outlet of the watershed stretching upstream was continued until the final location. The decision of suitable hydropower sites was taken based on set criteria (figure 7).

Selection of potential hydropower sites

The stream network generated by the ArcGIS tool using a 12m DEM and threshold value of 12000 closely follows the stream network extracted from the DEM map. The smaller the threshold value, the more detailed is the stream network generated by the ArcGIS interface. The model generates the stream network giving details of stream length and elevation difference for every stream in the study area.

Results And Discussion

In the present study, the discharge and elevation data has been used to locate feasible locations and their potentials. The potential power thus generated can save a lot of coal used in thermal power plants and thus restrict the emission of many greenhouse gases.

Estimation of hydropower potential for Gumara and Ribb Rivers

As stated in the methodology parts of this study the estimation of hydropower for both Gumara and Ribb Rivers were based on the extracted stream elevation and stream slope at each pixel or pixel by pixel in ArcGIS environment (figure 7). Then the extracted stream elevation and stream slopes were overlaid (figure 7b). The combination of the two selected streams (i.e. Gumara and Ribb rivers) describes the possible potential hydropower sites in the study area of Guna-Tana Landscape. A selected river reaches is divided in cross sections spacing 1000m for Gumara River and 2500m for Ribb River, these distances were chosen because of the variable topography in the study area. In order to determine the flow value at each cross section, using kriging interpolation techniques in ArcGIS environment was used according to the contribution area along the selected river reaches (figure 7). The point elevation value of each cross section is taken from the DEM; by extracting values to point the head values of all cells, were computed for both main rivers and allocates these values to the selected cross section. The maximum number of 20 hydropower potential sites are selected from both catchment for analysis; the selected sites are based on the availability of the head by evaluating the elevation of the streams, the steeper is the stream more is the availability of potential head, thus, for a given discharge higher is the power potentiality. However, for the stability point of view, too steep streams are not desirable. The knowledge of the geological characteristics of the sites would be required to investigate the steepness versus stability phenomena. Though in the present investigation such analyses are not done, the information on stream steepness may be useful for comprehensive planning for the utilization of the water resources. After extracting the elevation difference for the stream, we select 20 potential sites based on elevation difference for head determination. Figure 7b indicates the extracted elevation of the stream pixel by pixel that helps us for the selection of potential sites.

$$P = \rho g Q H \eta \qquad (1)$$

Where: P is power, ρ is the density of water (1000 kg/m^3

g is the gravity acceleration (9.81 m/s^2) and

η is the overall efficiency of the turbine or generator.

The mean discharge of Gumara River from 1990 up to 2017 and for Ribb from 1961 to 2007 years were used for the analysis.

Determination of Efficiency (η) and Turbine Types

From the graph (Figure 11), we can check the types of turbine based on head and discharge so the Francis turbine is in between Pelton turbine and Kaplan turbines. In this study, based on the available head determined from stream elevation in ArcGIS environment, we use Francis Turbine for both of Gumara and Ribb rivers.

If Head (m) < 45 m Kaplan turbine

If Head (m) between 45 - 250m Francis turbine

If Head (m) >250m Pelton turbine

In practical calculation based on the above head interval the efficiency for Pelton Turbine is 85 %, for Francis turbine is 90% and for Kaplan turbine is 90% (figure 11).

Sample calculation of Hydropower potential as presented in Tables 1 and 2 below.   From equation (1) P = ρηH*Q*g

1000*0.90*56*42.84*9.81 = <u>21181.12 KW</u>

In Gumara watershed noticed (Table 1) that streams are flowing within the elevation range between 1774 m and 2628 m from the downstream to the upstream of the watershed. Most of the area was covered under the elevation ranges from 1774m to 1917 m. on the other hand the elevation difference of River was ranges between 1760m and 2914m from the downstream to upstream of the catchment. The maximum area was covered under the elevation ranges of 1760m to 1887m, which was almost flat area of the study area (Table 2). The human habitation and their activities are mostly governed by the geographical locations. Thus, information regarding elevation of streams and its banks is linked with the competitive uses of water resources. The assessment of energy demands and their load Center would also depend upon the nature of habitation and its activities. The type of habitation in such altitude has been reported as very sparse.

Table 1. Hydropower potential of Gumara River

No	Turbine types	Head (m)	Discharge (m^3/s)	Gravity (m/s^2)	Density (kg/m^3)	Efficia (%)	Power (KW)
1	Francis Turbine	56	42.84	9.81	1000	90	21181.12
2	Francis Turbine	87	42.84	9.81	1000	90	32906.39
3	Francis Turbine	85	42.84	9.81	1000	90	32149.92
4	Francis Turbine	95	42.84	9.81	1000	90	35932.26
5	Francis Turbine	85	42.84	9.81	1000	90	32149.92
6	Francis Turbine	78	42.84	9.81	1000	90	29502.28
7	Francis Turbine	72	42.84	9.81	1000	90	27232.87
8	Francis Turbine	111	42.84	9.81	1000	90	41984.01
9	Francis Turbine	108	42.84	9.81	1000	90	40849.31
10	Francis Turbine	77	42.84	9.81	1000	90	29124.05

Table 2. Hydropower potential of Ribb River

No	Turbine types	Head (m)	Discharge (m^3/s)	Gravity (m/s^2)	Density (kg/m^3)	Efficiency (%)	Power (KW)
1	Francis Turbine	127	40.3	9.81	1000	0.9	45187.70
2	Francis Turbine	122	40.3	9.81	1000	0.9	43408.66
3	Francis Turbine	130	40.3	9.81	1000	0.9	46255.13
4	Francis Turbine	136	40.3	9.81	1000	0.9	48389.98
5	Francis Turbine	116	40.3	9.81	1000	0.9	41273.81
6	Francis Turbine	12	40.3	9.81	1000	0.9	4269.70
7	Francis Turbine	126	40.3	9.81	1000	0.9	44831.90
8	Francis Turbine	130	40.3	9.81	1000	0.9	46255.13
9	Francis Turbine	129	40.3	9.81	1000	0.9	45899.32
10	Francis Turbine	126	40.3	9.81	1000	0.9	44831.90

The potential hydropower sites identified on Ribb river was greater than the potential identified on Gumara river the reason was the topography of Ribb stream was suitable than that of Gumara river. From the above computed results, the maximum power on Ribb stream was 48,389.98 KW while on Gumara stream was 41,984.01 KW. Therefore, the development of strategies to improve the decision-making process for Hydropower planning and construction is of paramount importance to support renewable energy production with the minimal negative social environmental impacts. This need to improve decision making at the planning stage has been discussed worldwide as an effective way to balance the increasing demand for energy with biodiversity conservation and the protection of human welfare.

Conclusion

This study used information at the local level and a GIS-based tool to assess the hydroelectric potential in the Gumara and Ribb rivers in the Guna-Tana landscape. The result of the study indicates that the maximum hydroelectric potential reaches the sites in the rivers. The results of this work are the first step towards understanding the potential sites for energy supply and demand. The important parameters taken into account to carry out this study were topographic data (elevation, slope, flow direction, flow accumulation, stream orders) and hydrological data (river discharge) were evaluated and analysed by using GIS tools. The main factor for the identification of the hydroelectric sites in the study area was the calculation of the gross hydroelectric potential of the Gumara and Ribb rivers from parameters such as turbine efficiency, height difference, gravitational acceleration, discharge mean of the river for the years considered and the water density. The study concludes that there are twenty sites identified along the Gumara and Ribb rivers as potential sites for hydroelectric power generation.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interest

The authors declare that there is no competing interest in publishing this manuscript.

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Authors' contributions

Asirat Teshome intellectualise the study, collecting data, analysing and interpreting the data, and wrote the

Manuscript. Yinas Tibebu and Endalkachew Addis revised and edited the manuscript. All authors read and approved the final manuscript.

Availability of data and materials

The data sources used in this study includes USGS satellite images of the study area was downloaded from the respective website http://earthexplorer.usgs.gov , Alaska DEM with a spatial resolution of 12.5m was freely downloaded from website Alaska satellite facility's vertex.daac.asf.alaska.edu and The other datasets can be provided up on request.

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Figures

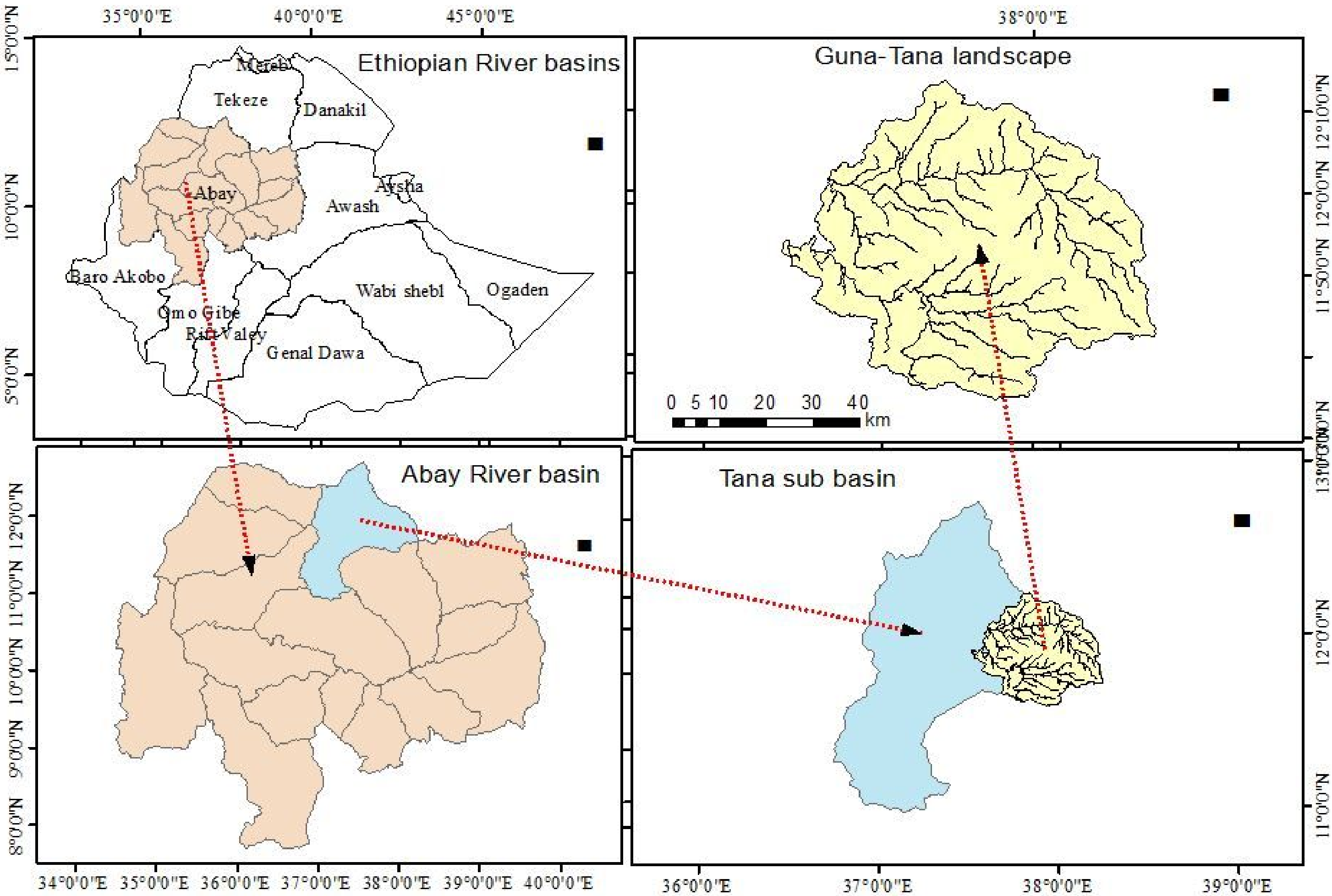
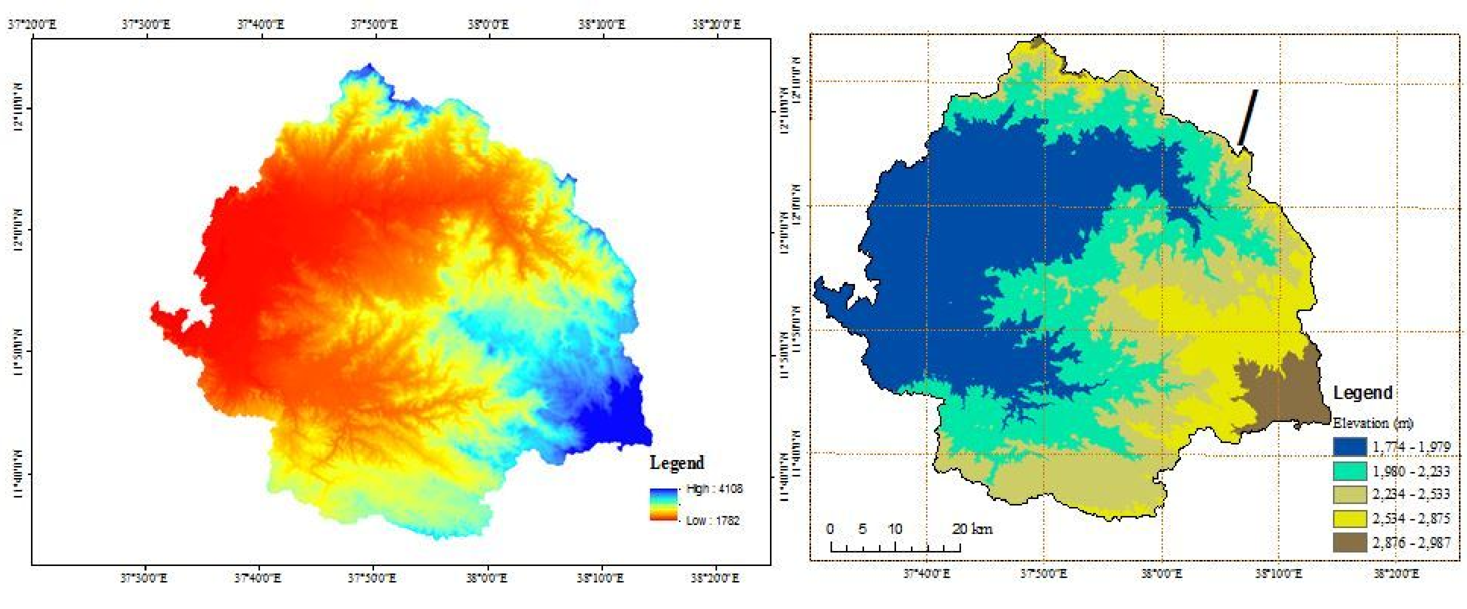


Figure 1

Location map of study area (Guna Tana Landscape)



(a) (b)

Figure 2

(a) DEM and (b) elevation difference of study area

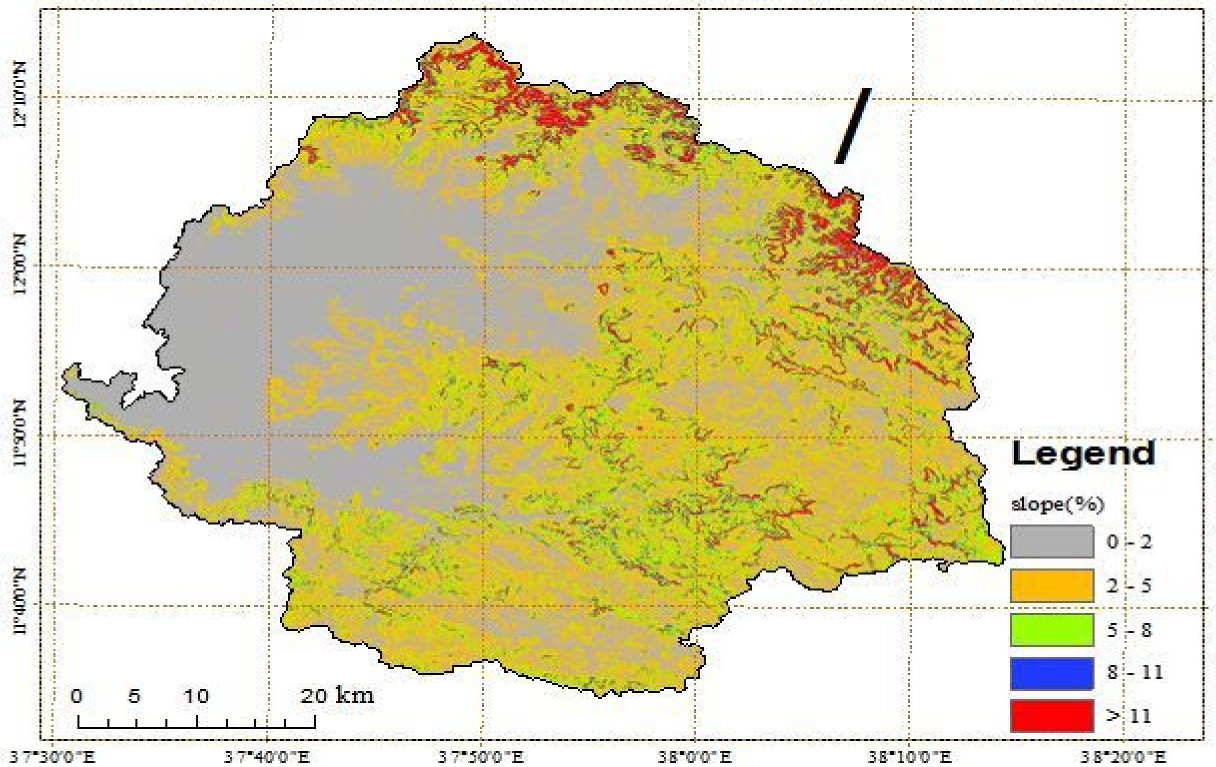


Figure 3

slope map Guna-Tana landscape

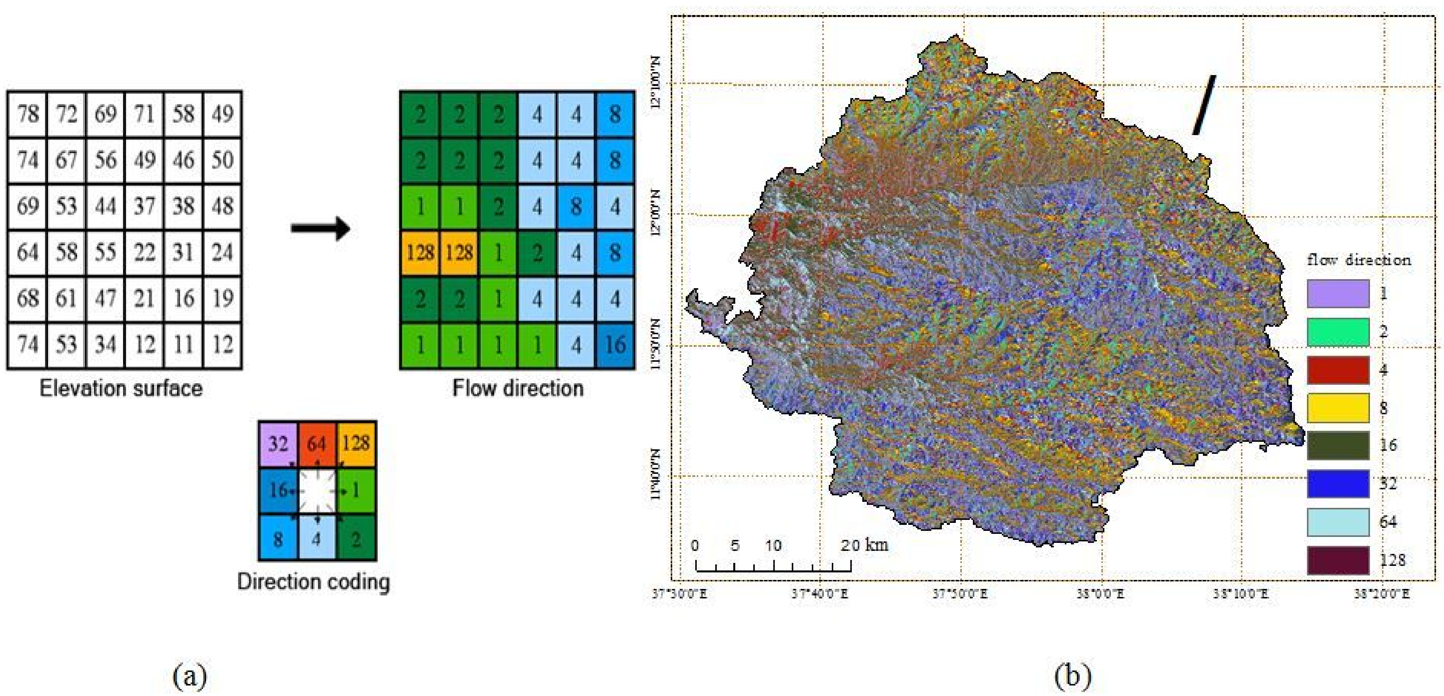


Figure 4

(a) Assigning flow direction value and (b) Flow direction map of study area

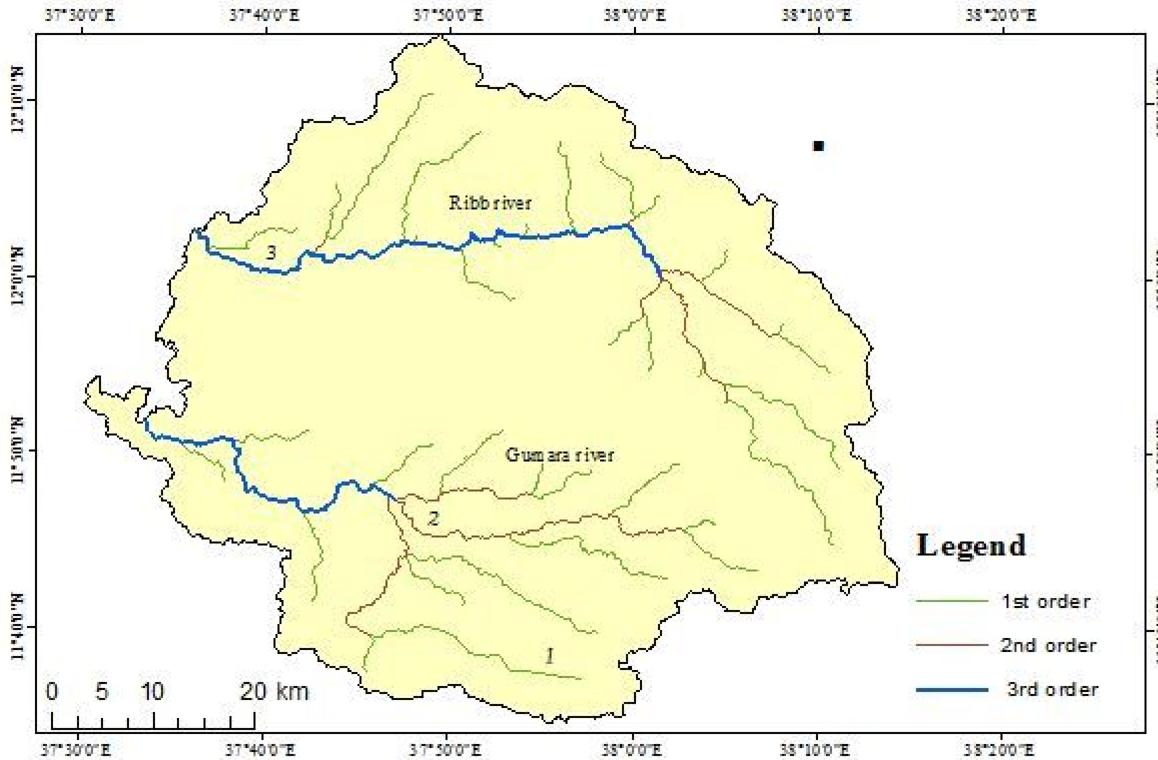


Figure 5

Stream order map of Guna-Tana watershed.

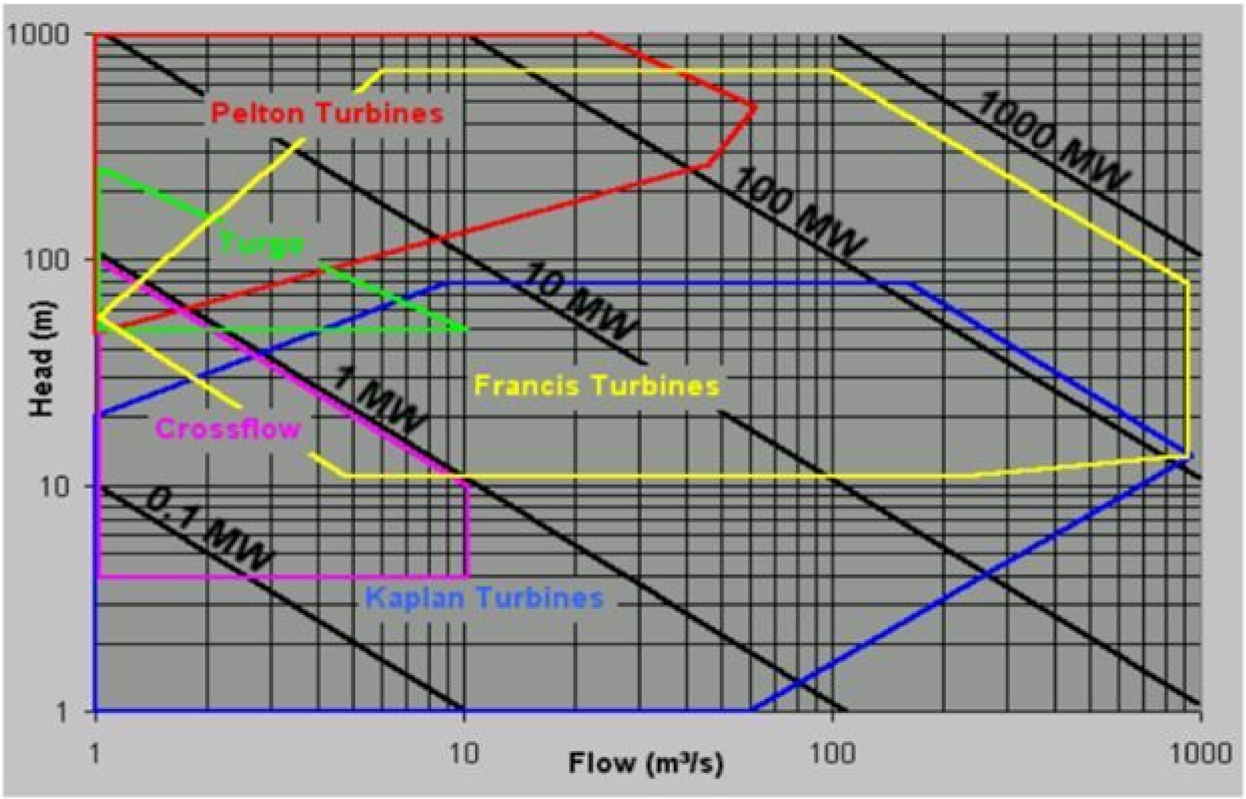


Figure 6

Graph shows flow versus head for turbine types

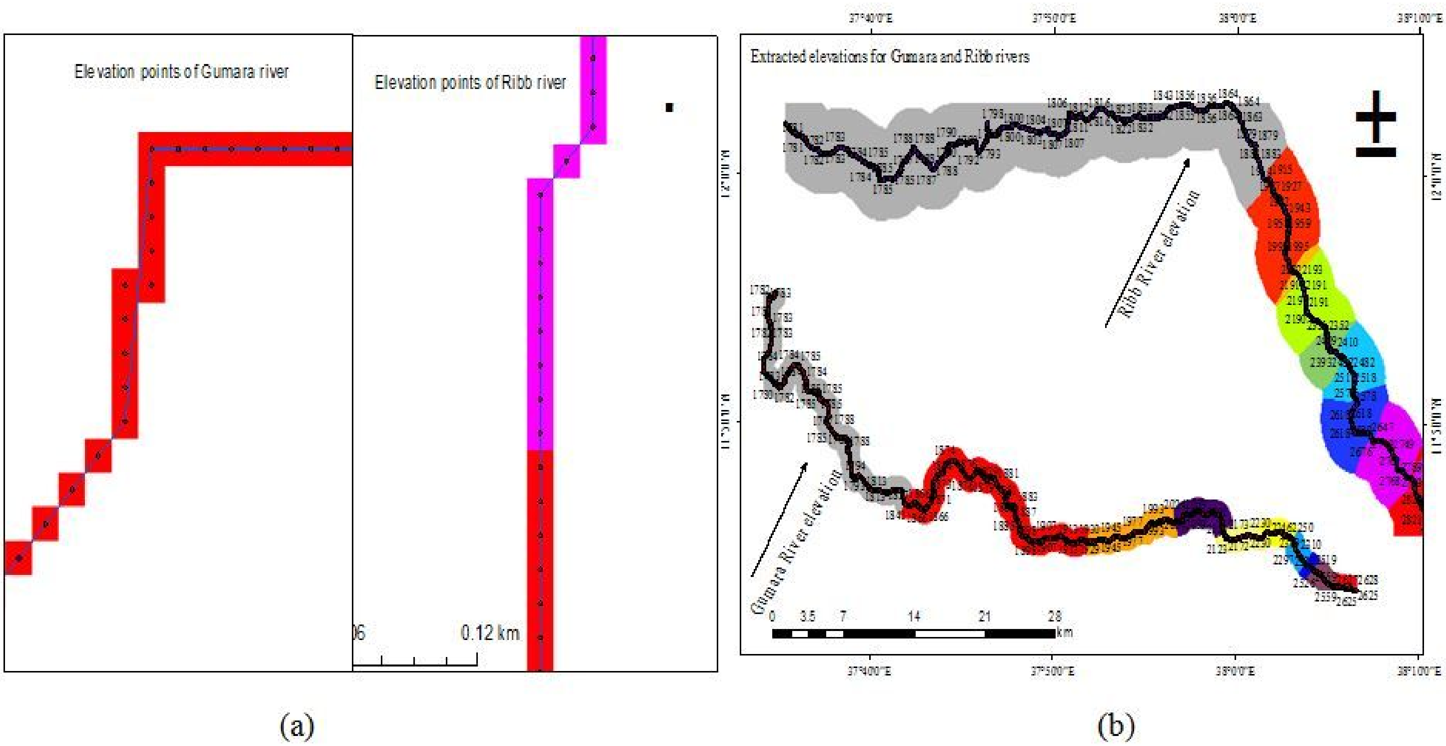


Figure 7

Elevation points and (b) Extracted elevation pixel by pixel for Gumara and Ribb rivers

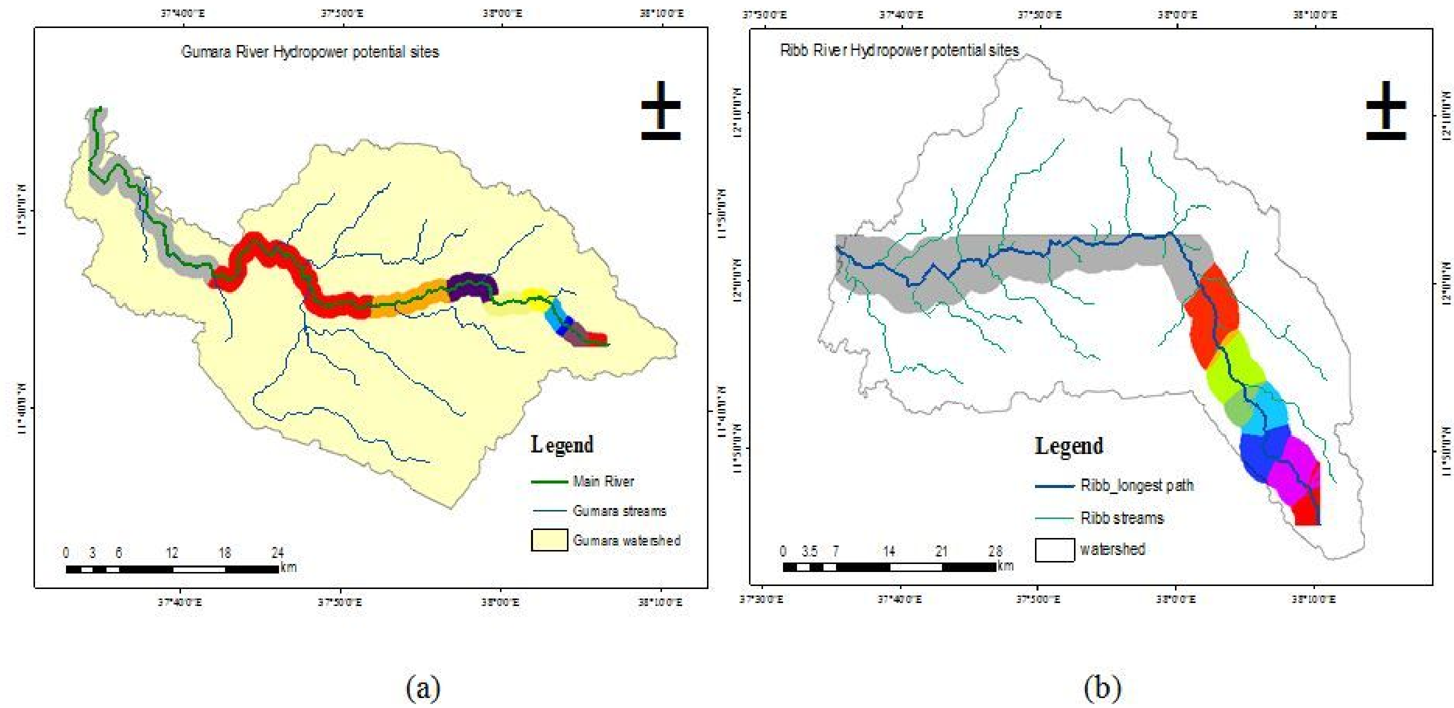


Figure 8

Maps of Hydropower potential sites on (a) Gumara River and (b) Ribb River

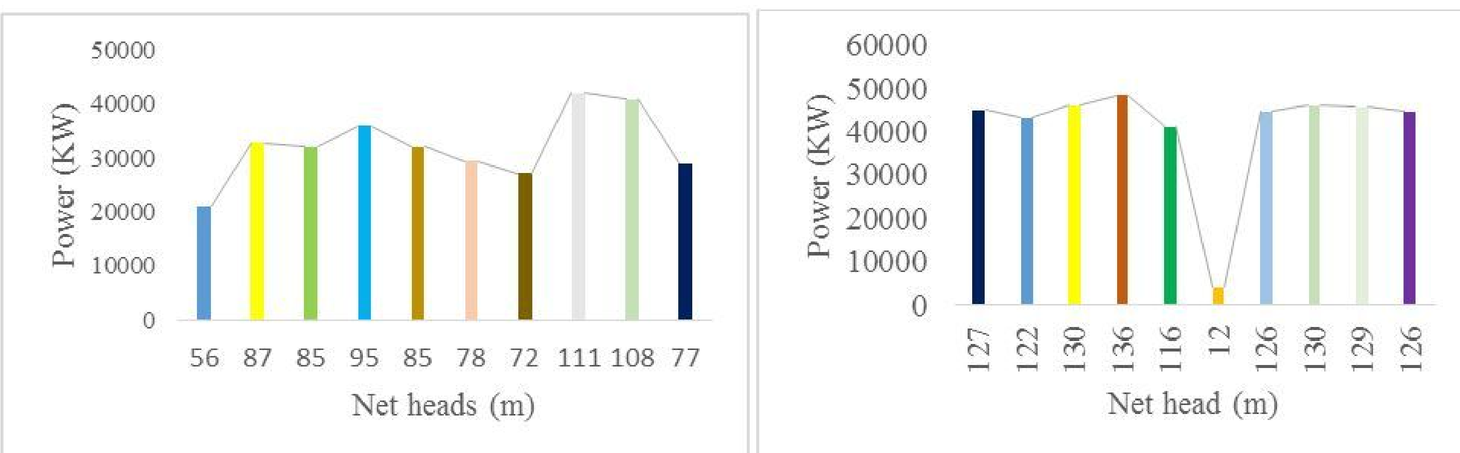


Figure 9

Graph of power potential versus net head along (a) Gumara river and (b) Ribb River