

# Technical Feasibility Assessment of Mini-Hydropower Development at Selected Sites in the Highlands of Ethiopia

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# Executive summary

Renewable energy sources are climate- and land-resource-smart development interventions. In Ethiopia, because of its topographic nature and high rainfall availability, mini-hydropower (MHP) is one of the most suitable renewable energy sources. However, it is variable in space and time, thus requiring accurate estimations regarding its potential for targeting investment. Because of a lack of discharge data and high-resolution topographic data, and also because most MHP sites are located in remote areas, the necessary information for developing MHP plants is not readily available. CIAT and Mekelle University, in collaboration with GIZ, conducted a technical feasibility study of some selected proposed sites in Amhara and Oromia regions of Ethiopia. To obtain the necessary information, an intensive field survey and hydrological modeling were conducted. The two important parameters for estimating power (head and discharge) were calculated from a field theodolite leveling survey and hydrological modeling at designated locations. The MHP component layout and geotechnical and basic socioeconomic information have also been documented for the 15 proposed MHP sites.

# 1. Introduction

The pressure on land for various purposes such as for biomass (particularly firewood and charcoal) and agriculture is the primary cause of land degradation in Ethiopia (Gebreselassie et al., 2016). Ethiopia has one of the lowest rates of access to modern energy services, whereby the energy supply is primarily based on biomass. About 94% of the total national energy consumption is derived from traditional biomass fuel (fuelwood, charcoal, dung, and crop residues) and only 4% is derived from modern energy sources such as petroleum fuels and electricity (Mondal et al., 2018). The more pressing problem is that, in some parts of the country, all vegetation, crop residues, and animal dung are used for household fuel consumption, with no residues to be added into agricultural landscapes, thus leading to health and land degradation problems. A large number of initiatives and programs aiming to improve soil health/fertility and land restoration implemented in Ethiopia in the past few decades have limited success because of this traditional biomass energy usage. Therefore, expansion of alternative renewable energy is not only useful from the energy efficiency perspective but is also important from the land degradation perspective and for increasing the success of sustainable land management activities in the country.

Energy is one of the key elements in the socioeconomic development of a nation. For the past decade, problems with energy supply have been increasing for different reasons, including the oil crisis, climate change, technical capacity limits, continuously growing demand, and restrictions on sales (Lajqi et al., 2016). One of these alternative sources is to generate electricity as close as possible to consumption demand by using renewable sources that do not cause environmental pollution. Hydro, wind, biomass, solar, and geothermal are among the most important renewable sources for energy generation (Nautiyal et al., 2011; Josel et al, 2014).

To solve these problems, electrification of rural communities is essential. Increasing the penetration rate of renewable energy (RE) sources such as small run-of-the-river (ROR) hydropower, solar power, and wind power would diminish the dependency on traditional biomass and decrease the pressure on land for an energy source, that is, it would allow all organic matter (vegetation, crop residues, and animal dung) to remain to improve soil fertility. One of the most important advantages of RE is the decrease in $CO_2$, thus contributing to the effort to combat climate change as the damage from climate change is quite diverse. This, in turn, facilitates the efforts of Ethiopia to fulfill national strategies such as Climate-Resilient Green Economy (CRGE) and regional and global agendas such as the AFR100 initiative (Abegaz et al., 2020). Moreover, increasing the production of RE has strong synergistic effects on the Sustainable Development Goals (SDGs) by providing energy for making progress on several goals. Out of the 17 SDGs, most of them, such as ending poverty, improving health and education, combating climate change, and protecting forests, have a high demand for renewable energy. For instance, the expansion of RE in the rural areas of Ethiopia will ensure healthy lives by decreasing indoor pollution that could be produced by charcoal and firewood, thus improving the welfare of women as the burden of indoor air pollution is currently placed disproportionally on them. This would improve gender equality and girls' education.

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Because of its geographic location, Ethiopia is endowed with various renewable energy sources such as natural gas, hydropower, wind power, solar power, and geothermal. The main source of RE is large hydropower plants (94%) such as Koka, Awash, Fincha, Beles, Tekeze, etc., including the new Grand Ethiopian Renaissance Dam, whereas small hydropower has been given no attention at all although the amount of energy produced by it is important in several places. In addition, most of the villages and towns that are remotely located largely rely on traditional biomass energy sources for cooking and heating. Large hydropower systems can be complex and can bring a range of socioeconomic and environmental risks (Botelho et al., 2017; Kaunda et al., 2012). The need for power and the negative effect of traditional power systems requires a new method of electrification in rural areas. This new method could exploit the potential of renewable energy such as hydro, wind, and solar or a combination of the three. Because of the natural topography and water resources, many locations are suited for hydropower generation without the construction of large dams (e.g. run-of-the-river (ROR) kind of design) and at relatively low cost. Hence, micro-hydropower is an important small-scale source of energy. Small (mini or micro) hydropower can be a solution in terms of causing minimal environmental impact and minimal investment demand, and can also be developed off-grid for rural society. The highlands and rift escarpments of Ethiopia are often associated with high topographical variability and they receive relatively high rainfall. Moreover, many of these areas have perennial streams/rivers that could provide suitable conditions for local power generation. Therefore, mini-hydropower (MHP) schemes are the appropriate solution to the demand for power as these require a small capital investment and can be completed in a short period of time, with minimum adverse environmental impacts (Raguvanshi et al., 2008). MHP is also useful for electrifying the rural community without developing expensive grid infrastructure in the rural community. Rural electrification and energy development are also key components in the Climate-Resilient Green Economy (CRGE) strategy of Ethiopia. In the country, however, the development of MHP is at the early stage. According to a 2010 German Agency for Technical Cooperation Report, small hydropower and MHP are not yet developed on a larger scale in Ethiopia. Only three small hydropower schemes exist: in Yadot (0.35 MW), Dembi (0.80 MW), and Sor (5 MW), with a cumulative installed capacity of 6.15 MW.

Cognizant of the importance and the status of MHP development, we have conducted a feasibility study on micro-hydropower at remote sites of Ethiopia as a showcase for the high potential of ROR energy in the Ethiopian highlands.

# 2. Objectives

The main objective of this study was to estimate the key feasibility indicators of MHP using important variables such as flow duration curve, water station layout, penstock height, and highest water level recorded at each site and to finally estimate possible power generation at 15 selected sites in the highlands of Ethiopia.

# 3. Study locations for MHP feasibility

Although the country has huge potential for ROR hydropower generation, we estimated the potential for selected sites. All the sites are in Amhara and Oromia regions and most of them are located in the Upper Blue Nile basin. Those sites were selected from hundreds of potentially feasible sites reported by farmers throughout the Ethiopian highlands. Following a brief description of what the potential MHP sites would be for the woreda (district) energy office, they collected the possible ROR sites that could generate hydropower. In most cases, farmers reported many sites where traditional power generation existed to drive traditional mills using the natural river flow. Other sites were reported because of the level of discharge and the topographic drop-off of the river cross-sections. Out of hundreds of sites reported in Amhara and Oromia regions, we selected 15 based on their accessibility (Figure 1 and Table 1).

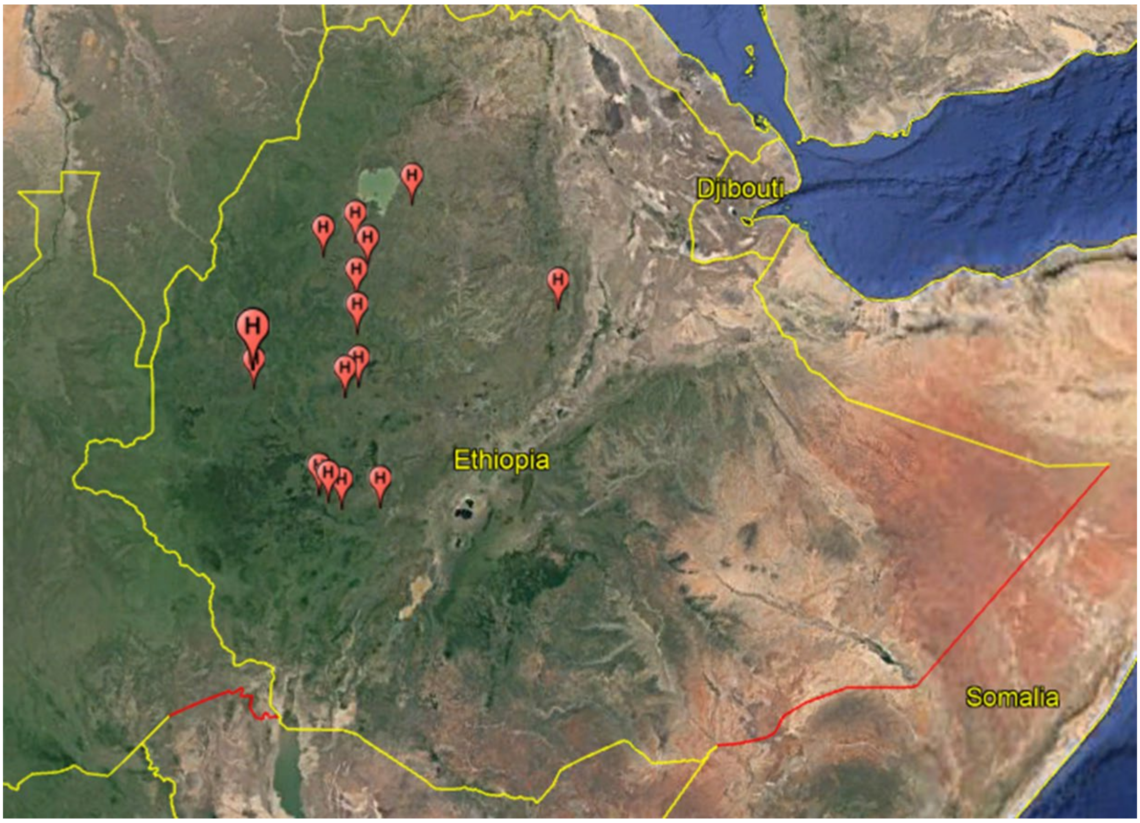



**Figure 1.** The location and spatial distribution of the 15 MHP designated sites.

**Table 1.** List of rivers and locations for which the feasibility study was conducted.

| ID | River | Latitude | Longitude | Elevation (masl) | No. of households within 1.5 km |
|---|---|---|---|---|---|
| **1** | Gumera | 11.7567102 | 37.79045274 | 1,915 | 400 |
| **2** | Geshe Abay | 11.23108582 | 36.98720813 | 2,077 | 420 |
| **3** | Timbil | 11.02861151 | 36.53269035 | 1,716 | 327 |
| **4** | Engrin | 10.88601525 | 37.16339016 | 2,430 | 252 |
| **5** | Fetam | 10.44391687 | 37.00588668 | 1,947 | Very few in 1.5 km radius |
| **6** | Gereb | 10.29141956 | 39.85483578 | 2,087 | 345 |
| **7** | Agaro/Naso | 7.739656921 | 36.4881892 | 1,910 | 1,000 |
| **8** | Elkete Gobe | 7.625730545 | 36.61217925 | 2,005 | 430 |
| **9** | Waro | 7.529779688 | 36.80704255 | 1,933 | 500 |
| **10** | Omo Beya | 7.544586723 | 37.34549526 | – | 210 |
| **11** | Welege | 9.953710334 | 37.01862726 | 2,228 | 300 |
| **12** | Gibe | 9.213521724 | 37.03939469 | 1,841 | 500 |
| **13** | Idris | 9.073447156 | 36.85123688 | 1,826 | 170 |
| **14** | Dilla | 9.458046099 | 35.5462043 | 1,741 | 300 |
| **15** | Barudemeti | 9.191589374 | 35.56529814 | 1,503 | – |

# 4. Approaches and methodologies

The hydropower potential at any site can be calculated as (François et al., 2018)

$$P(t)= \eta_H ghp\ q(t,i) \qquad (1)$$

where $P(t)$ is the power generating capacity of an MHP site (in kW), $\eta_H$ is the efficiency of the generator (no units), $g$ is the acceleration of gravity ($m^3/s^2$), $h$ is the falling height (m), $\rho$ is the water density ($kg/m^3$), and $q(t,i)$ is the water flow through the turbines ($m^3/s$). Although the other parameters are constant, the two important parameters in this equation need accurate estimation are the falling head *(h)* and the water flow available at the site ($q(t,i)$). The methodology for estimating these two important parameters and other related information is described in the following sections.

## 4.1 Calculation of total and net head

The gross head is one of the key parameters for the design and construction of MHP as it governs the calculation of power to be generated. The elevation difference between powerhouse and forebay is gross head ($H_g$). To estimate net head ($H_n$), we used the following formula (Okot, 2013):

$$H_n = H_g - H_{los} \qquad (2)$$

where $H_g$ [m] is the gross head and $H_{los}$ [m] is head losses due to penstock and gate construction. Although this can be measured and estimated case by case, we used an average value of 1.5 m loss for all sites based on field observations. To obtain the gross head, we conducted a survey using theodolite leveling differences for accuracy.

## 4.2 Measurement of water flow and construction of flow duration curve

Discharge ($q(t,i)$) in equation 1 is a key in the MHP feasibility study. It can be obtained from a survey at a specific time of the year. In this survey, we used a current flow meter to obtain one-time instant discharge, particularly representing low flow. However, these data do not represent the whole spectrum of the hydrological properties at the designated sites. The flow duration curve (FDC), which is the graphical representation frequency or the fraction of time during which a specified magnitude of discharge is equal or exceeded, provides precise information regarding the long-term availability of enough water flow to generate hydropower at the designated cross-section (Searcy, 1959; Vogel and Fennessey, 1994). When proposed MHP sites were near discharge gauges, we used these historical discharge data to develop the FDC. However, in most cases, historical discharge measurements were not available or discharge measurement sites were far from the designated MHP sites. When discharge measurements were not available, we used a hydrological model that was calibrated in the same basin and used its estimation at the location of interest. We used a hydrological model (specifically, a JGrass-NewAge model; Formetta et al., 2014), which was already calibrated for the upper Blue Nile basin by Abera et al. (2017), and its performance was much better than that shown by previous modeling results. To drive the model, we used satellite precipitation data (Beck et al., 2017) and simulated discharge at each river link. The inputs for the hydrological model are precipitation and energy budget and the outputs are the discharge and actual evapotranspiration. The optimized rainfall-runoff model was used to estimate discharge for each river link node. Detailed information on the modeling procedure can be found in Abera et al. (2017).

Once discharge was estimated from either the historical record or hydrological model simulation as described above, the FDC was constructed at the MHP sites. In our case, out of 15 sites, only three had gauge measurement (Gilgel Abay, Fetam, and Gibe) near the proposed sites. For those sites, the FDC was developed from measured data. For the rest, we used the model to forecast discharge at the point of interest. To construct the FDC, streamflow observation needs to be ranked in descending order, $qi$ to $qN$, where $i$ is the rank of an observation and qi and $qN$ are the largest and smallest streamflow observations, respectively. Then, each ordered observation $(qi)$ is plotted against its corresponding duration, $Di$, including in the exceedance probability of $qi$. Two types of FDC are available: the period-of-record FDC and annual FDC. In the period-of-record FDC, the complete period of record is used to compute a single FDC of streamflow, leading to steady state or long-term probabilistic statements concerning streamflow exceedances (Searcy, 1959). The annual FDC is an approach that is useful for making probabilistic statements about a given calendar (water) year (Vogel and Fennessey, 1994; Cigizoglu, 2000). Annual FDC (AFDC) is more useful than the period-of-record FDC because it provides the hypothetical median AFDC and its confidence interval (Vogel and Fennessey, 1994). Hence, we used the AFDC for this report. The ***mean*** probability $p$ for a given Q is given by

$$mean_p = sum\ (P_{AFDC})/number\ of\ years$$

In this report, the 16 years (1994 to 2009) of daily simulated discharge were used to construct annual FDC. Once AFDC was constructed, we obtained various flow summary indices and characteristics at a given location. Although the whole FDC provides the whole spectrum of streamflow (max, Q90, Q70, Q50, and min), the information can be used to determine the nature of flow and define the designated flow for MHP generation. The percentage of time that a stream is at zero flow conditions defines whether the river is intermittent or perennial (Smakhtin, 2001). In general, a minimum discharge exists below which there is no power generation to supply the environmentally required flow of downstream area (RenÖfÄlt et al., 2010). Similarly, there is no power production above a certain flow threshold because of potential damage to the power plant because of discharge exceeding the safety threshold discharge. Here, we set the minimum at 5% and maximum at 95%.

## 4.3 Assessment of the socioeconomic conditions of the sites

The design and construction of mini-hydropower require evaluation of the number of people living around the area, their main sources of income, and estimates of power demand. The core socioeconomic data required for MHP assessment are the location of an MHP site and its administrative location; the nature of the population distribution around the site, particularly within a 1.5 km radius; the main income of local communities; a list of public institutions such as schools, churches, and clinics; and the distance to the nearest electrical grid. Regarding the distance from the MHP site to the electricity-connected village, we used two data sources: (1) data from Google Earth, which are included in the main text of the report, and (2) information from local elders, which is reported in a summary table at the end of the report. The location and its administrative names were obtained from a field GPS survey and interviews with local officials (kebele leaders or local water and energy experts), respectively. The method to obtain the number of households within 1.5 km was a combination of local interviews and Google Earth. The other socioeconomic data such as local income, local community interest in the MHP project, and overall condition of the site were collected through focus group discussions with the local elders.

## 4.4 Measurement of water level at flood

Estimation of the water level at flood is critical for the design and location of MHP. The location of the powerhouse should avoid the level and section where the water flows to avoid scouring and to prevent inundation of the powerhouse during high flows. For all the sites, the water level at flood was estimated using a combination of interviews with local residents (mainly elders who knew the flood history of the stream/river) and field observations of flood marks at the site by the team of experts, and these included traces of flooding and vegetation boundary. Based on this information, the highest water level at the site was recorded, pegged, and photographed as evidence to be used for detailed design and construction of the MHP plant.

## 4.5 Selection of the best site and general sketch of MHP water station

During this survey, the nature of the streambed, morphology of the river/stream (bends, etc.), natural features along the stream (soil, rock boulders, etc.), competing use of water, and any slope stability and siltation problems were assessed. The best site was pegged and photographed, and the exact location was recorded using GPS. On a detailed map (supported by photographs), a layout of the water station was produced with key justifications as to why this site was the best option. The final selection of the best site was to be participatory, which involves representatives of local communities.

## 4.6 Assessment of the general geotechnical conditions of the sites

Most MHP sites are located close to hilly/mountainous areas. Evaluation of the major soil/rock types, their geotechnical behavior, and any potential slope stability is important for the safe design and construction of the MHP. Along this line, we used the following approaches to assess the stability and suitability of the sites: (1) assessment of overall slope stability, foundation conditions, flooding, erosion/sedimentation problems, etc., of the major MHP components; (2) overall assessment of the water tightness of the soils/rocks along the main canal route and any slope stability problems as well as siltation/sedimentation risks; and (3) any competing or complementary issues involving assessment of any competing use of water for irrigation in upstream areas and the risk of decreasing flow to the plant, and any complementary opportunities such as linking irrigation development with power generation as some of the river diversions are planned to be upstream of the MHP components while the command/irrigable area is downstream of the MHP site. In the case of complementary opportunities, the diverted water could be used to generate hydropower as well as for irrigation.

# 5. Results of the survey

## 5.1. Estimation of head, flow, and geotechnical and socioeconomic conditions at each MHP site

In this section, we have reported the layout, flow duration curve, and general socioeconomic conditions for each site. The general context such as location of institutions and their distance from the MHP site is estimated using Google Earth maps. Sketches and photographic evidence on MHP layout were used. The FDC is presented to portray flow properties. Geotechnical information about each site is presented in a concise table form. At the end of the section, additional summary information on core data for each site is presented in Table A1.

### *5.1.1. Gumera MHP site*

This site is located in south Gonder in Fogera woreda, specifically in Guramba kebele. The site is not accessible by car, requires at least 30 minutes of travel on foot, and is surrounded by sparse villages. Figure 2 shows the general situation regarding its proximity to villages and public institutions (schools, clinics, and churches). The distance to the nearest school (Dire elementary school) is 2.6 km (Figure 2). The Tewodros church, to the east, is 0.73 km from the site. Although power is not available currently, the nearest electrical grid is in Guramba kebele center, which is about 3 km away. The villages within 1.5–2.0 km from the Gumera MHP site are geotagged in Figure 2 (in blue polygon) and the population is densely distributed, with about 300 households. The main income in the area is crop production, with rice, millet, sorghum, and safflower being the main crops cultivated.

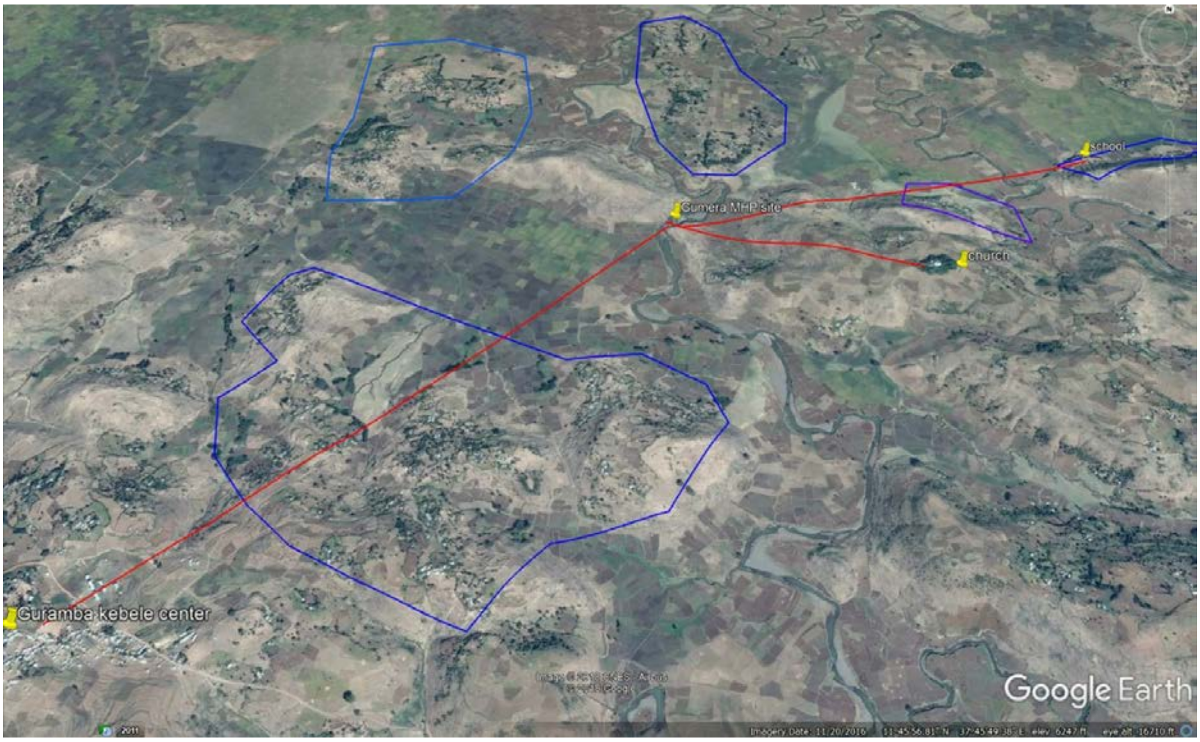



**Figure 2.** Overall site conditions, villages, and institution locations at Gumera MHP site.

Schematic and panoramic views of the Gumera MHP site are shown in Figure 3, which clearly indicates the layout for each component for the MHP plant. The maximum head measured is 15.388 m (with net head of 13.888 m). The powerhouse is safe from flooding as it is located far from the flood level (Figure 3). At the powerhouse location, there is 1.0 to 1.5 m of soil, below which is a good foundation of weathered rock.

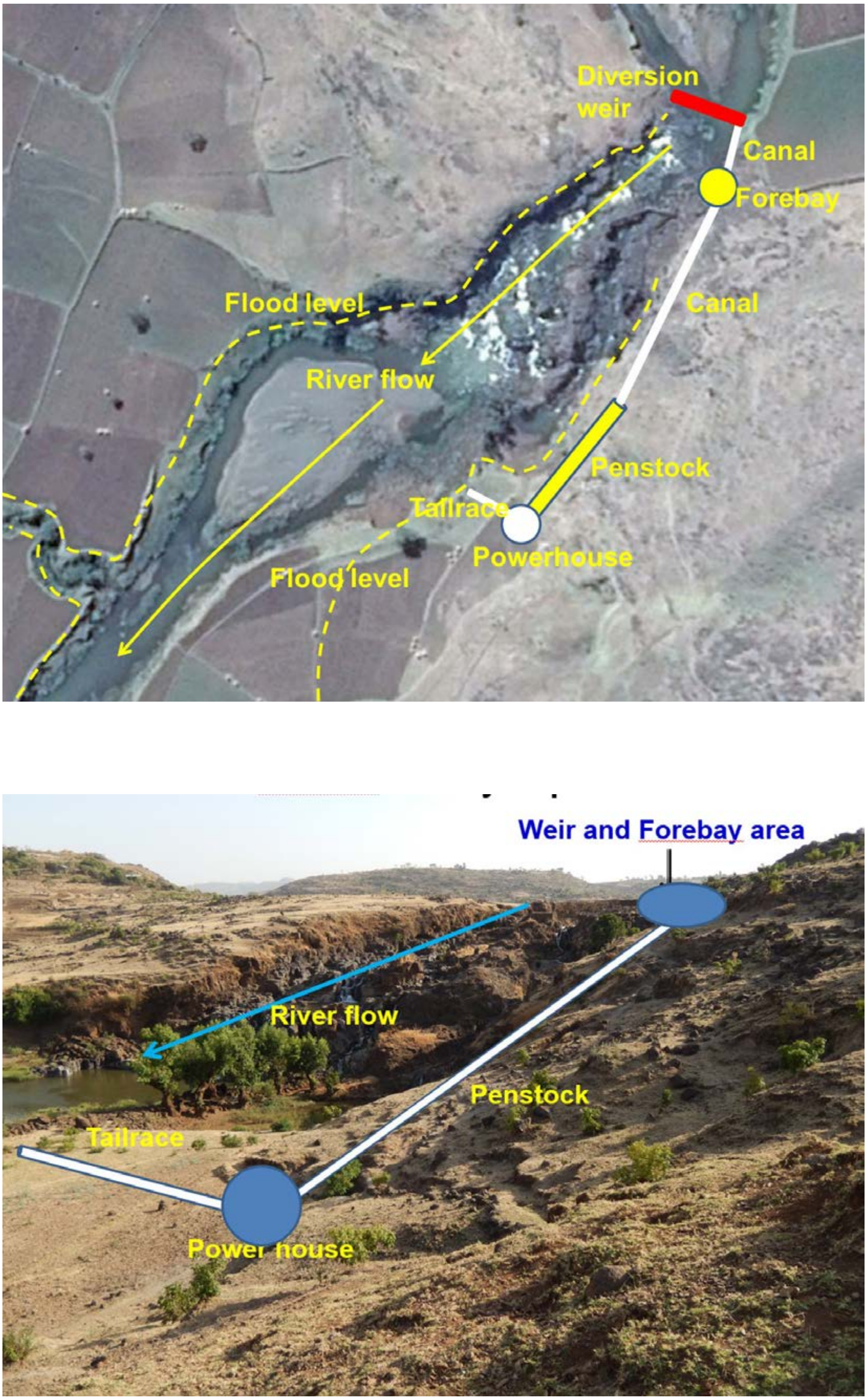



**Figure 3.** Schematic view (above) and panoramic view (below) of Gumera MHP site, Amhara region, Ethiopia.

The in situ discharge measurement for Gumera River is located far downstream from the proposed MHP site after two major rivers joined Gumera River. Thus, measured discharge cannot be used to develop the FDC curve. Hence, we used model simulated discharge data. Figure 4 presents the AFDC estimated from 16 years of discharge simulations. The median year FDC (red line in the middle) presents the flow characteristics for the most typical year occurring at the Gumera MHP site, showing that 10% of the time the annual flow exceeds 24.6 $m^3/s$, while 50% of the time it exceeds 1.3 $m^3/s$. Table 2 presents various statistics of the FDC. The measured discharge during mid-March 2018 was 0.275 $m^3/s$, which corresponds to 80%, indicating that 80% of the time the annual flow can be higher than this value. The local hydroclimatic conditions during the measurement period (2nd week of April 2018) could be considered representative of low flow and sunny days.

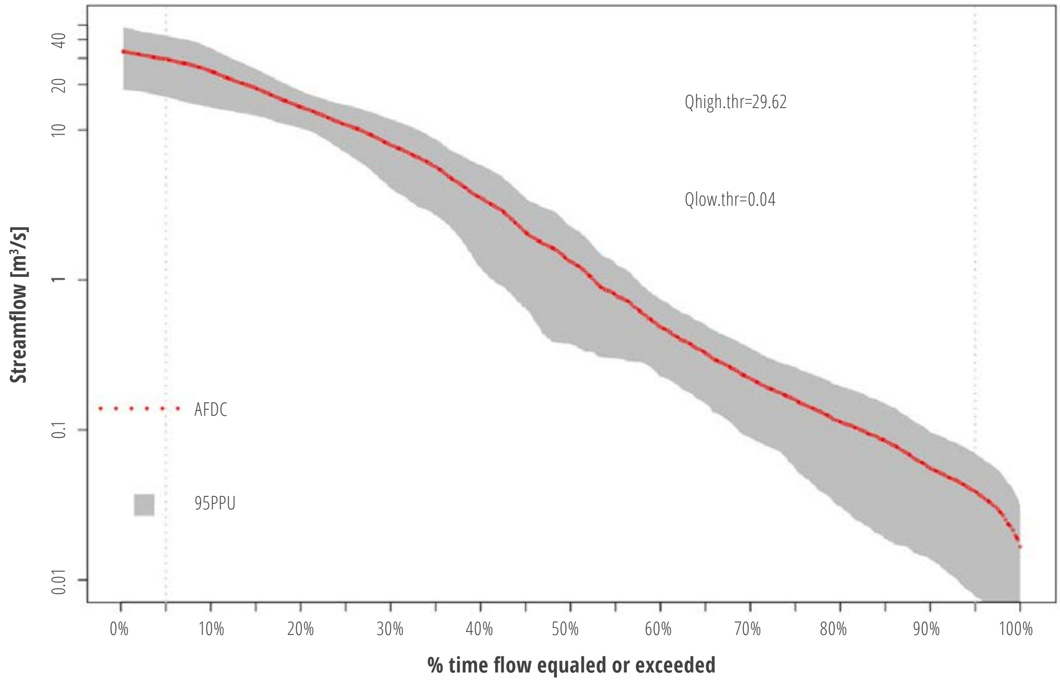



**Figure 4.** Flow duration curve at Gumera site: the red line represents the long-term median year while the gray line represents the 95% confidence interval due to annual variability.

**Table 2.** Measured and flow duration-based discharge (minimum, maximum, 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentile) of mean daily FDC at Gumera MHP site.

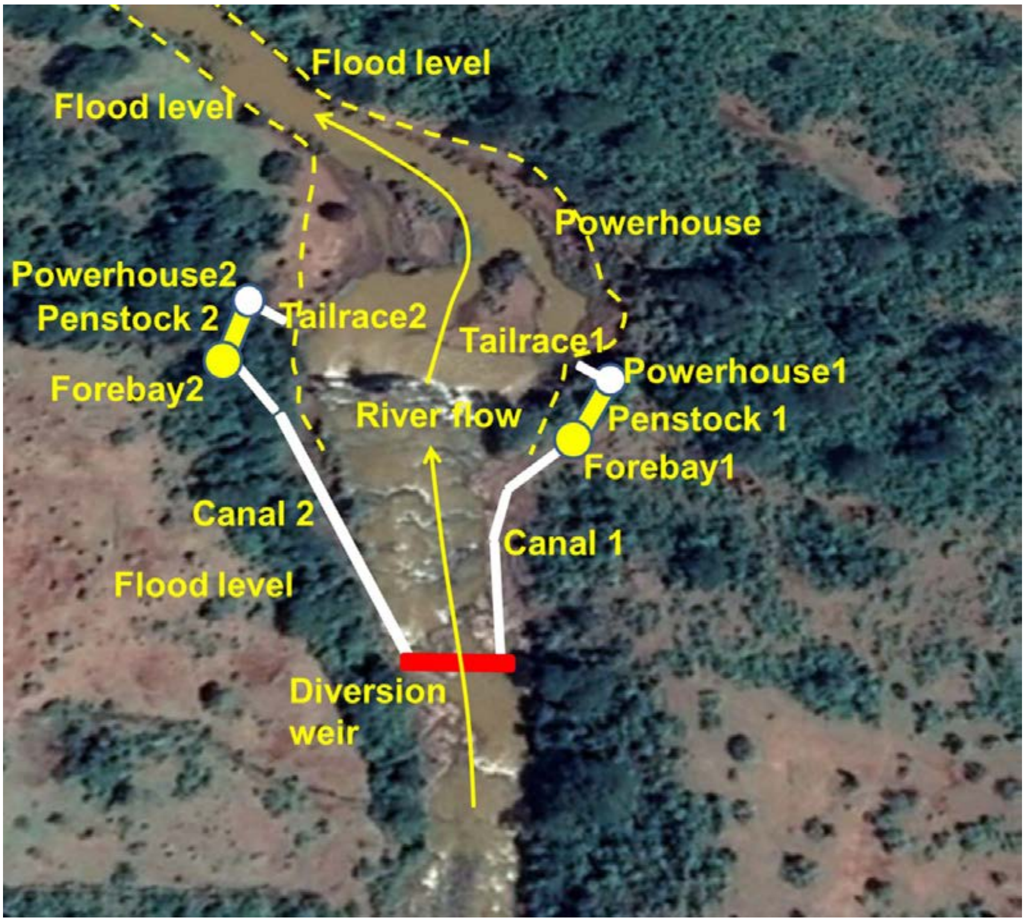
| % | Measured | FDC estimated | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | max | 5 | 10 | 25 | 50 | 75 | 90 | 95 | min |
| Q value | 0.276 | 35.0 | 29.58 | 24.60 | 10.86 | 1.33 | 1.19 | 0.086 | 0.039 | 0.017 |

## *5.1.2. Gilgel Abay MHP site*

Gilgel Abay (sometimes called Gish Abay) is located in Awe Zone, Amhara region. The social institutions such as schools and churches are relatively far (from 2 to 6 km) from the MHP site. Figure 5 shows the spatial distribution of the villages around the MHP site using Google Earth. Within a 1.5 km radius of the site are about 420 households. Two institutions (one elementary school and one church) are available in this range. The main economic activity is farming, with maize, millet, and teff being the dominant cereal crops growing in the area. The nearest electrical grid is in Ligaba (Hamusit) Town, which is about 5 km away.


**Figure 5.** Overall site conditions, villages, and institutions located near Gilgel Abay MHP site.

For the MHP plant, we identified two alternatives: one from the right and one from the left. Figure 6 presents the schematic and panoramic views for the two sites. Comparing the two, the right side is preferable for two reasons: (1) it has higher total head (10.52 m) than the left (8.99 m) and (2) its workability is much better than the left side of the river because of the nature of the slope. The left side, on the other hand, has an advantage of an extremely steep slope, thus decreasing energy dissipation by penstock friction, which in return would increase total power generation.




Site 2: Right Side: Gish Abay

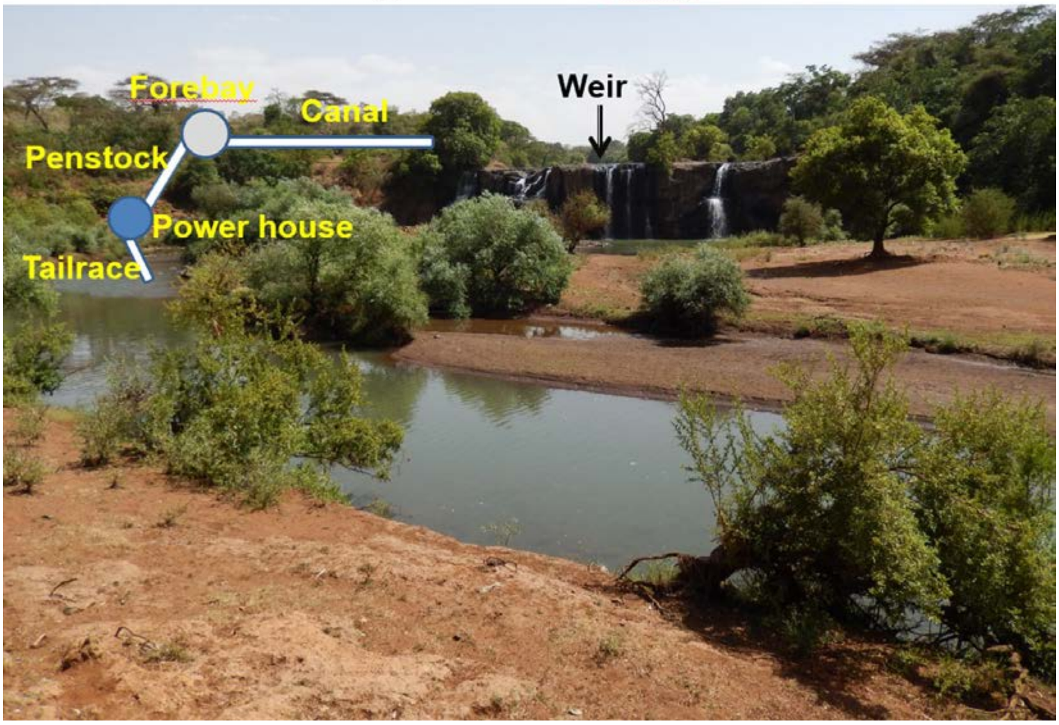



**Figure 6.** Schematic view (above), right-side option panoramic view (middle), and left-side option panoramic view (below) of Gilgel Abay MHP site, Amhara region, Ethiopia.

Gelgel Abay discharge measurement is near the proposed site; thus, we used historical gauge measurement to estimate the FDC. Figure 7 shows the FDC at the Gelgel Abay MHP site. The red line in the middle is the median FDC, while the gray around the line is the 95% uncertainty of the estimates. The median year FDC (red line in the middle) presents the flow characteristics for the most typical year occurring at the Gelgel Abay MHP site and the gray around the line is the 95% uncertainty of the estimates. The median line shows that 10% of the time the annual flow exceeds 37.54 $m^3/s$, while 50% of the time it exceeds 4.47 $m^3/s$. Table 3 presents various statistics of the FDC of Gelgel Abay. The measured discharge in March 2018 was 0.52 $m^3/s$, which is a little less than the FDC minimum. During the measurement period, the local atmospheric conditions could be considered as representative for a low flow hydroclimatic regime.

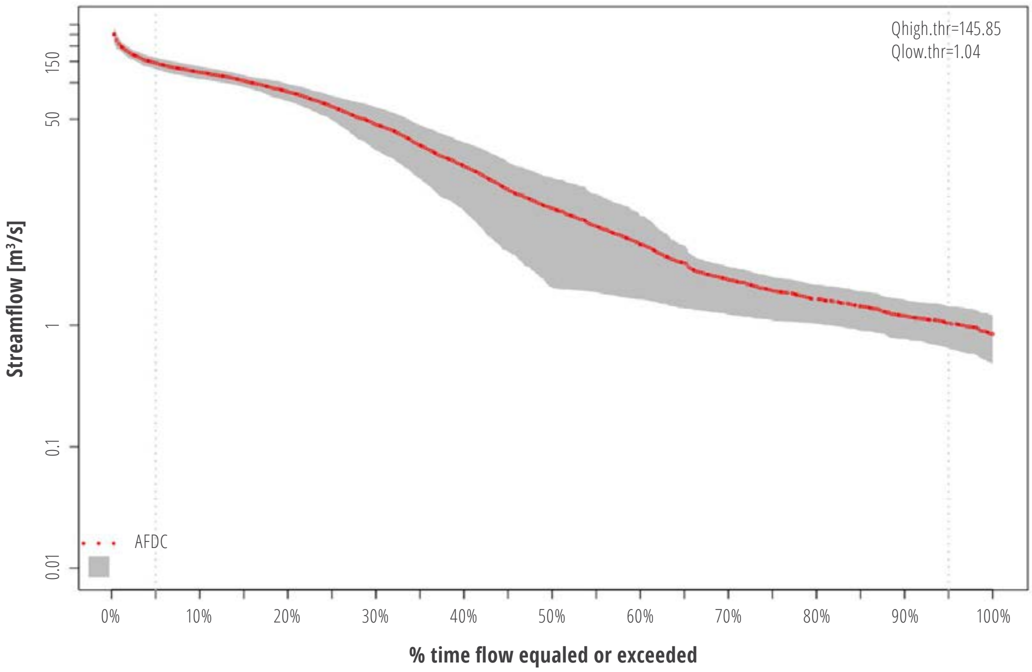



**Figure 7.** Flow duration curve at Gilgel Abay site: red line represents the long-term median year while the gray line represents the 95% confidence interval due to annual variability.

**Table 3.** Measured and flow duration-based discharge (maximum, minimum, 95th, 90th, 75th, 50th, 25th, 10th, and 5th percentile) of mean daily FDC.

| % | Measured | FDC estimated | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | max | 5 | 10 | 25 | 50 | 75 | 90 | 95 | min |
| Q value | 0.52 | 289.62 | 145.47 | 121.80 | 63.67 | 9.24 | 1.93 | 1.19 | 1.03 | 0.85 |

## 5.1.3. Tinbil MHP site

This site is located in Guangue woreda, Awe Zone, Amhara region. It is relatively sparsely populated, with an estimated 327 households within a 1.5 km radius. Farming is the main economic activity. Maize, teff, and millet are the common crops in the area. There are two elementary schools and one church within the specified radius (see Figure 8: blue villages, red institutions). The nearest grid-connected town is Tiru Brehan (although the grid is not functional now), while the main grid-connected city is Chagni, which is 10 km from the site.

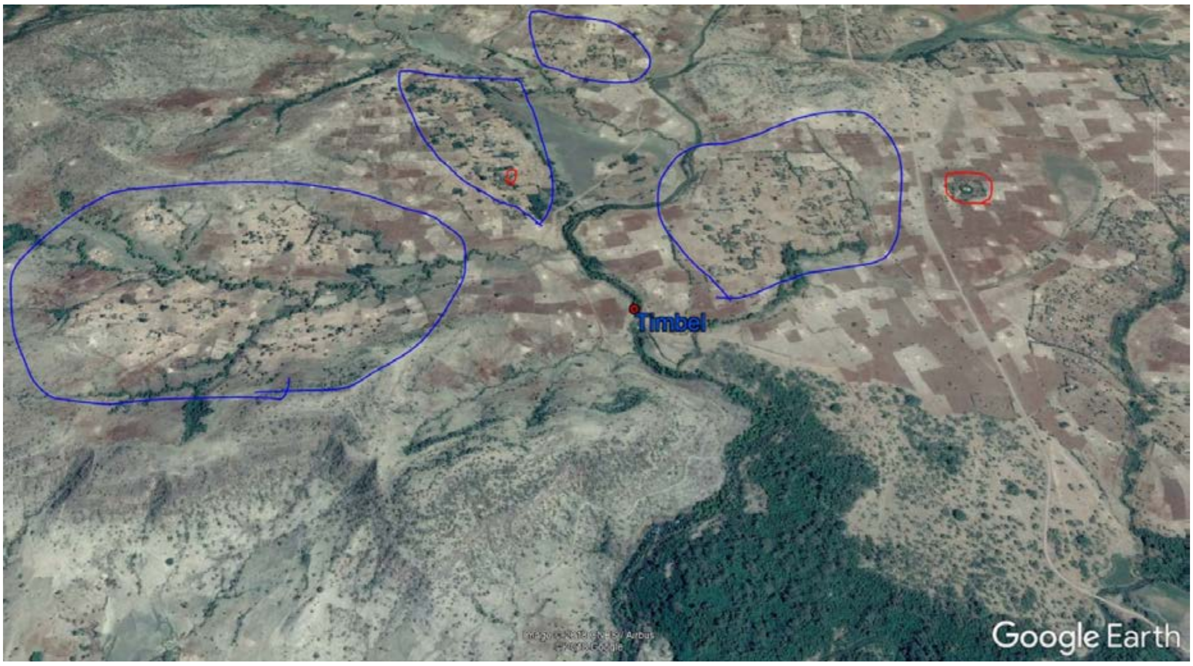



**Figure 8.** Overall site conditions, villages, and institution locations at Tinbil MHP site.

Regarding the MHP site itself, we identified both sides of the river and measured the head for both. The total measured head was 13.678 m and 10.828 m for the right and left side of the river, respectively. The right side, the canal from the diversion weir to the forebay, requires a deep cut. Hence, we identified the left side as the best option for the MHP plant (see Figure 9).

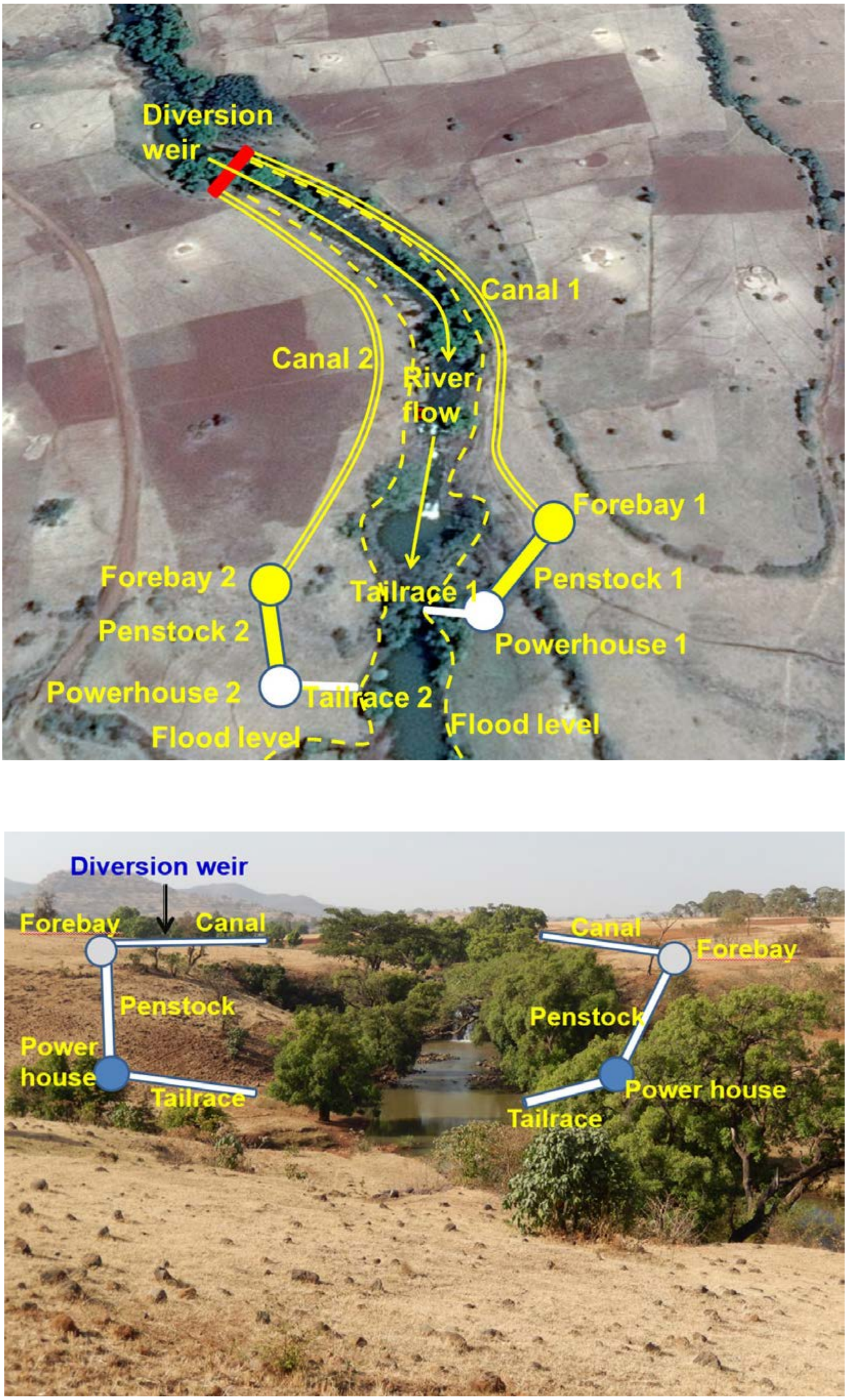



**Figure 9.** Schematic view (above) and panoramic view (below) of Tinbil MHP site, Amhara region, Ethiopia.

The FDC and some selected FDC statistics for the Tinbil MHP site are shown in Figure 10 and Table 4, respectively. The maximum and minimum flow estimated from the model results are 53.72 $m^3/s$ and 0.10 $m^3/s$, respectively. The 50% exceedance is 5.93 $m^3/s$. The measured discharge data in March 2018 marked 0.39 $m^3/s$, which corresponds to 83% of exceedance (Table 4). During the measurement period, the local atmospheric conditions could be considered as representative for a low flow hydroclimatic regime.

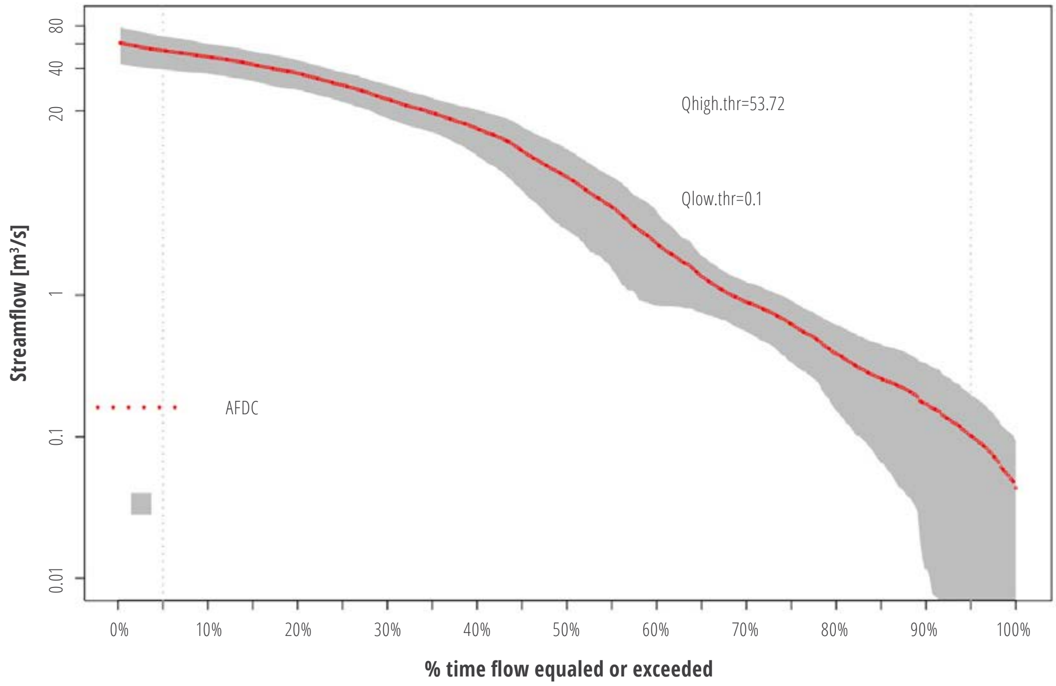



**Figure 10.** Flow duration curve at Tinbil site: red line represents the long-term median year while the gray line represents the 95% confidence interval due to annual variability.

**Table 4.** Measured, and flow duration-based discharge (maximum, minimum, 95th, 90th, 75th, 50th, 25th, 10th, and 5th percentile) of mean daily FDC at Tinbil site.

| % | Measured | FDC estimated | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | max | 5 | 10 | 25 | 50 | 75 | 90 | 95 | min |
| Q value | 0.39 | 60.32 | 52.53 | 45.96 | 25.51 | 5.93 | 0.39 | 0.09 | 0.05 | 0.02 |

## 5.1.4. Engrin MHP site

The Engrin River proposed MHP site is located in Sekela woreda, west Gojjam, Amhara region. The area is relatively densely populated (252 households estimated). Within a 1.5 km radius are two elementary schools and two churches (Figure 11). Crop cultivation is the main livelihood, with barley, potato, maize, and wheat being the common crops. The nearest grid-based electricity access to the site is Agut, which is about 5 km away.


**Figure 11.** Overall site conditions, villages, and institution locations at Engrin MHP site.

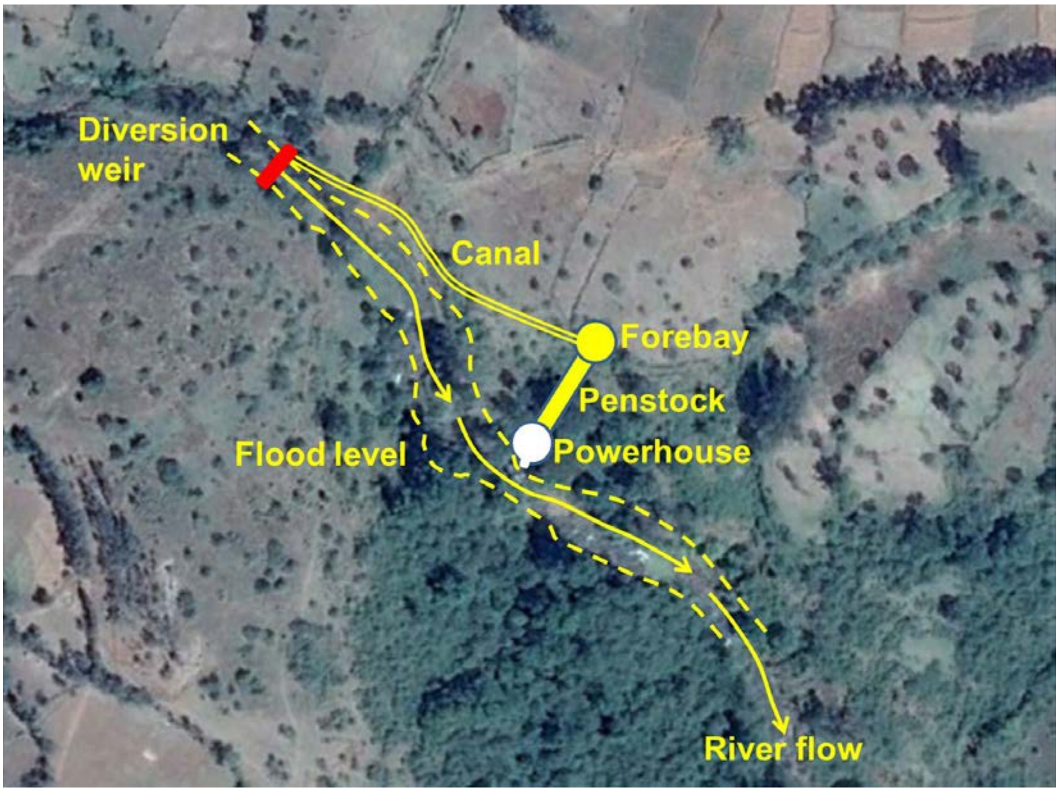




**Figure 12.** Schematic view (above), panoramic view for diversion site (middle), and penstock (and powerhouse) site (below) of the proposed Engrin MHP site, Amhara region, Ethiopia.

The river channel created a series of cataracts and provided an opportunity to find a large head (40.42 m). The diversion and powerhouse sites are pegged in Figure 12 (middle and below, respectively). Regarding flow information, Figure 13 shows the whole spectrum of flow distribution using the FDC. The maximum flow and minimum flow observed were 62.87 and 0.01 $m^3/s$. The measured discharge was 0.16 $m^3/s$, which falls in the 83% range of the FDC (Table 5). During the measurement period, the local atmospheric conditions could be considered as representative for a low-flow hydroclimatic regime.

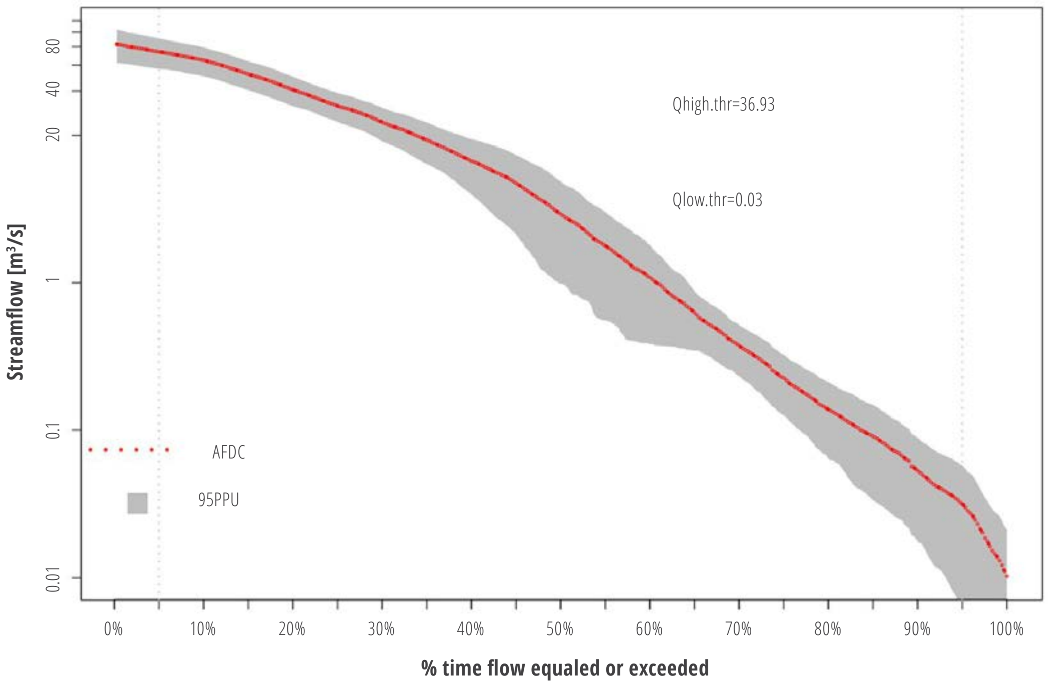



**Figure 13.** Flow duration curve at Engrin site: red line represents the long-term median year while the gray line represents the 95% confidence interval due to annual variability.

**Table 5.** Measured and flow duration-based discharge (maximum, minimum, 95th, 90th, 75th, 50th, 25th, 10th, 5th percentile) of mean daily FDC at Engrin MHP site.

| % | Measured | FDC estimated | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | max | 5 | 10 | 25 | 50 | 75 | 90 | 95 | min |
| Q value | 0.16 | 42.08 | 36.86 | 32.37 | 15.88 | 2.93 | 0.23 | 0.05 | 0.03 | 0.01 |

### *5.1.5. Fetam MHP site*

This site is located in Bure woreda, west Gojjam, Amhara region. No household resides within the 1.5 km radius (Figure 14). However, within 3 to 4 km, there are about 700 households. The nearest town to accessing an electrical grid is Kuch, which is about 4.5 km from the site. Crop production (maize, wheat, and pepper) and livestock rearing are the livelihoods of the local people. Although not within a 1.5 km radius, public institutions such as two elementary schools and three orthodox churches exist within a 4 km radius. According to our discussion with regional and woreda water and energy experts, the region is developing an irrigation plan, soon to be implemented, diverting water from the highland (above the escarpment) and irrigating the lowland plain areas along the right side of the river from the proposed MHP site.

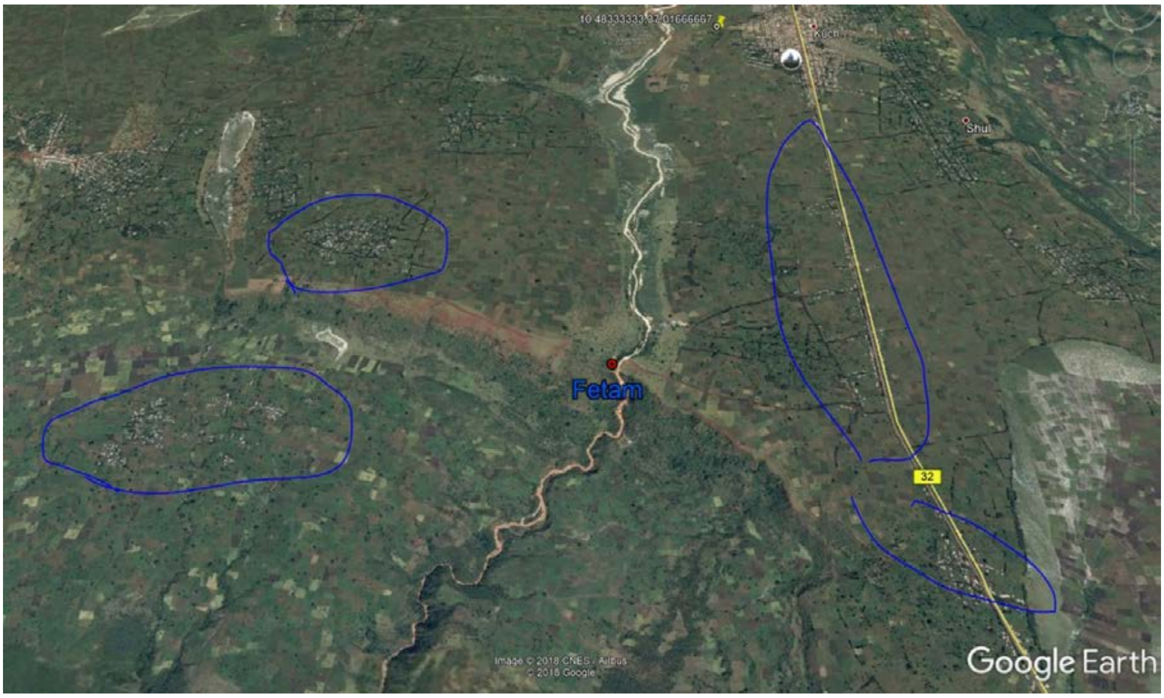
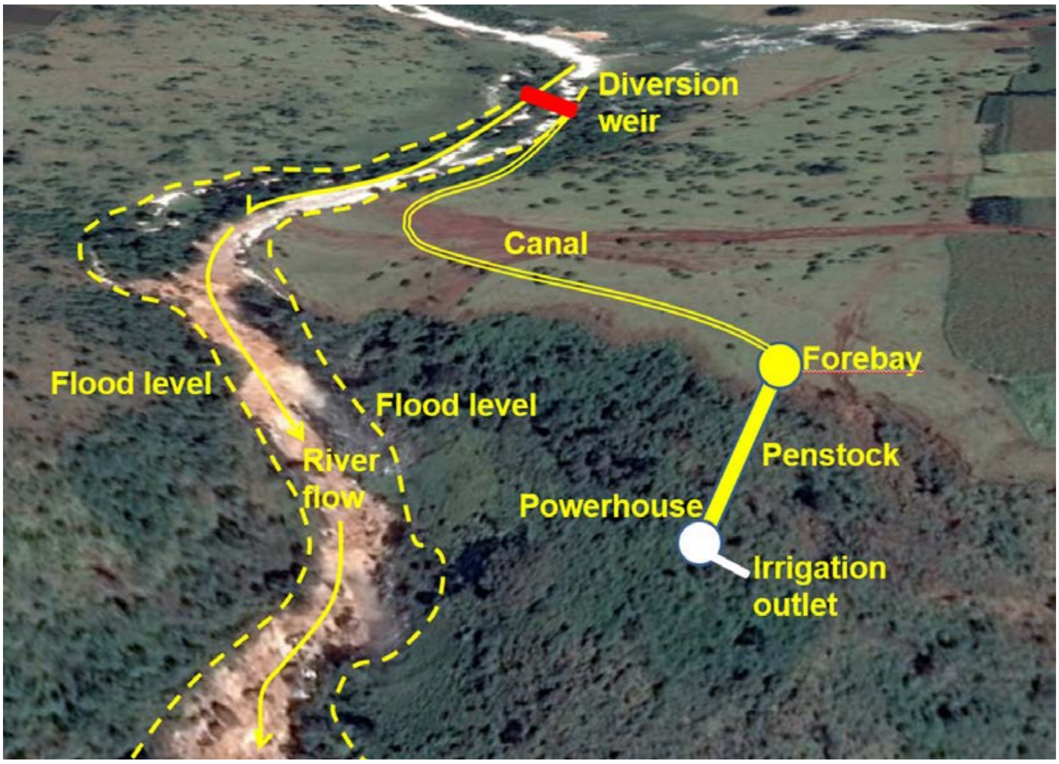



**Figure 14.** Overall site conditions, villages, and institution locations at Fetam MHP site.

Figure 15 shows a detailed sketch and panoramic view. The penstock passes through a slope that is dominated by debris materials (boulders, overhangs, some rockfalls, etc.), which need (a) provision of rockfall protection including provision of a protection wall, removal of overhangs at the early phase of construction by properly estimating the contributing area to rainfall, and taking necessary measures during construction; (b) removing debris/blocks along the penstock: the foundation should be on a stable stratum; and (c) placing the foundation of the powerhouse on a stable stratum (removing debris/blocks/soil) to a depth of 2–3 m.



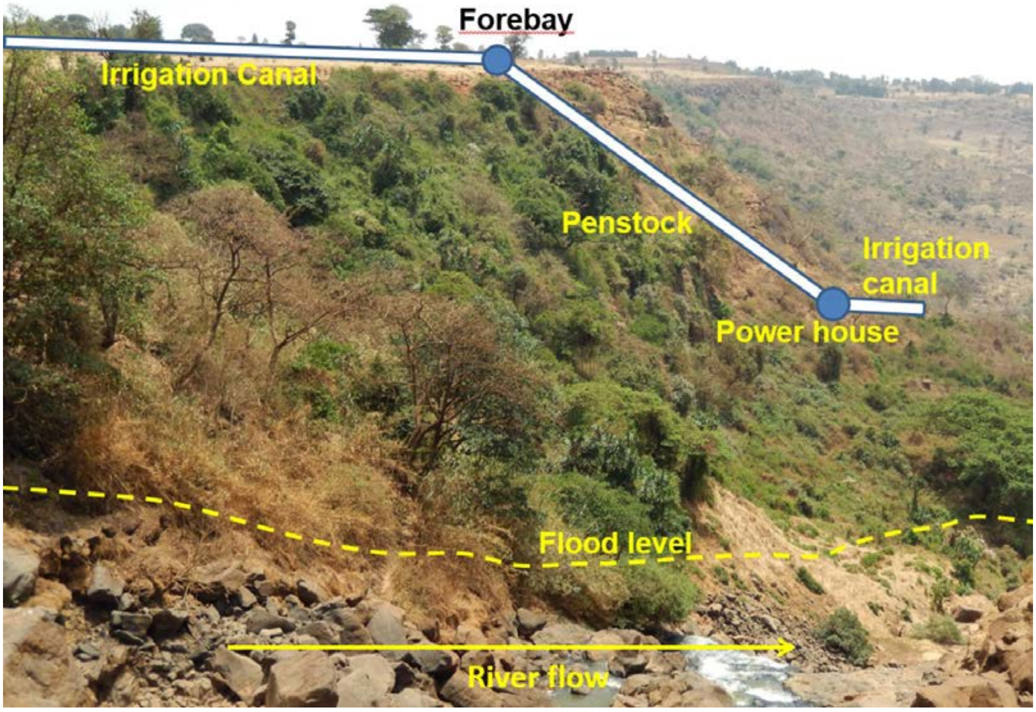




**Figure 15.** Schematic view (above) and panoramic view and penstock (and powerhouse) site (below) of the proposed Fetam MHP site, Amhara region, Ethiopia.

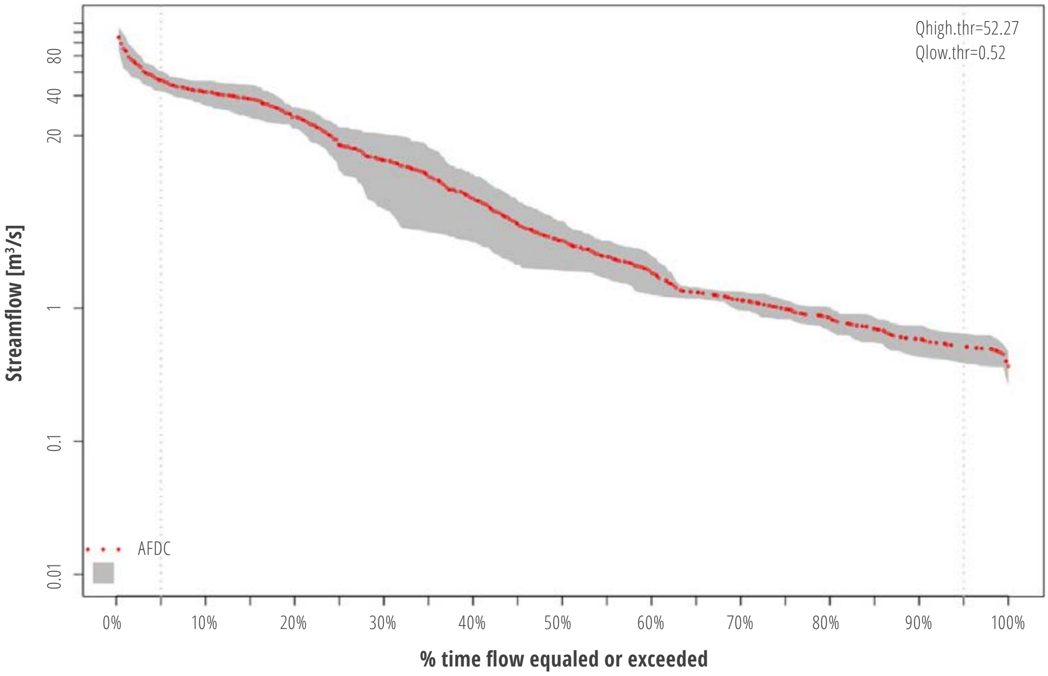



**Figure 16.** Flow duration curve at Fetam site: red line represents the long-term median year while the gray line represents the 95% confidence interval due to annual variability.

The maximum flow observed was 124.4 m³/s, while the minimum observed in 16 years of simulation was 0.04 m³/s (Figure 16). The 50th percentile of exceedance is 6.86 m³/s. Measured discharge during the field survey (mid-March 2018) was 2.57 m³/s (Table 6).

**Table 6.** Measured and flow duration-based discharge (maximum, minimum, 95th, 90th, 75th, 50th, 25th, 10th, and 5th percentile) of mean daily FDC at Fetam MHP site.

| % | Measured | FDC estimated | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | max | 5 | 10 | 25 | 50 | 75 | 90 | 95 | min |
| Q value | 2.57 | 124.40 | 52.25 | 42.66 | 16.94 | 3.26 | 0.99 | 0.59 | 0.52 | 0.37 |

## 5.1.6. Gereb MHP site

The total population size that would be served if the MHP were established is represented by four villages (Achefer, Gereb, Liamba, and the Metqoria kebele center), which constitute 345 households (Figure 17). According to the local farmers and local government experts, the main economic activity for the area is farming, with teff, sorghum, and wheat being the three main crops. The public institutions that would be greatly benefited by the MHP services are (1) the elementary school (grades 1 to 8) that is located 1.8 km from the site and (2) the kebele center (Metqoria), the nearby health center, and the two churches (one in Metqoria and the second in Liamba Village). The nearest electrical grid is about 10 km away.

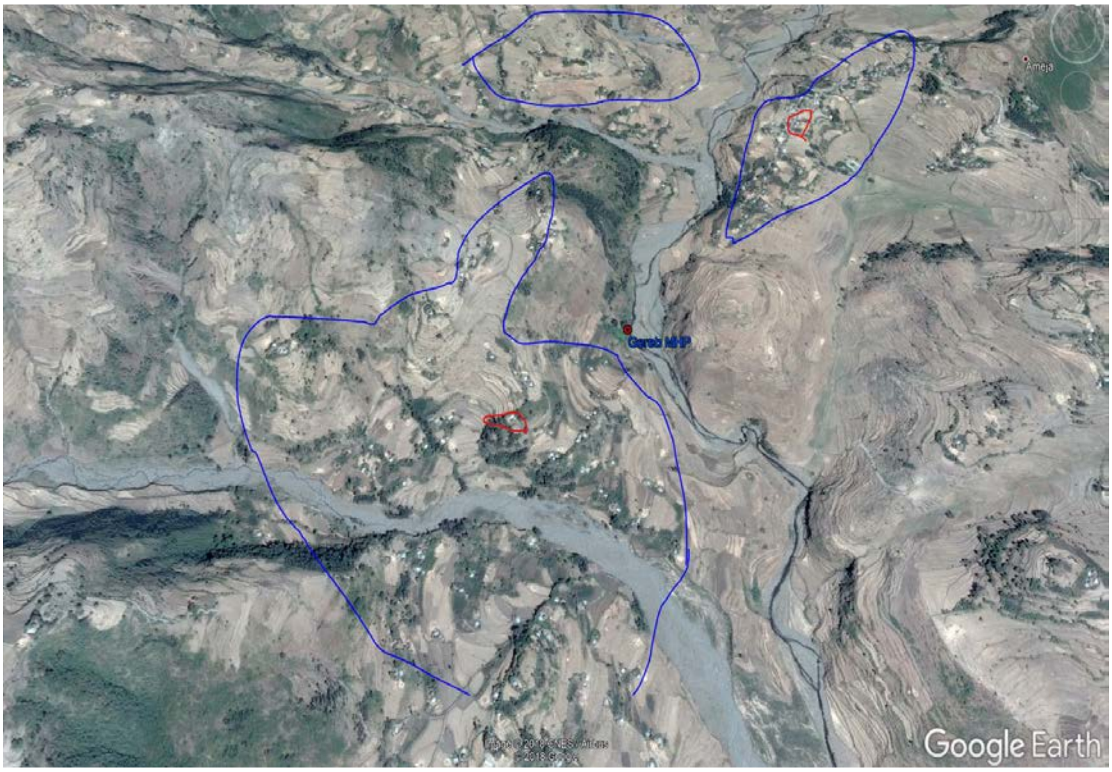



**Figure 17.** Overall site conditions, villages, and institution locations at Gereb MHP site. The blue polygon at the upper right is the kebele center, where small local business activities exist.

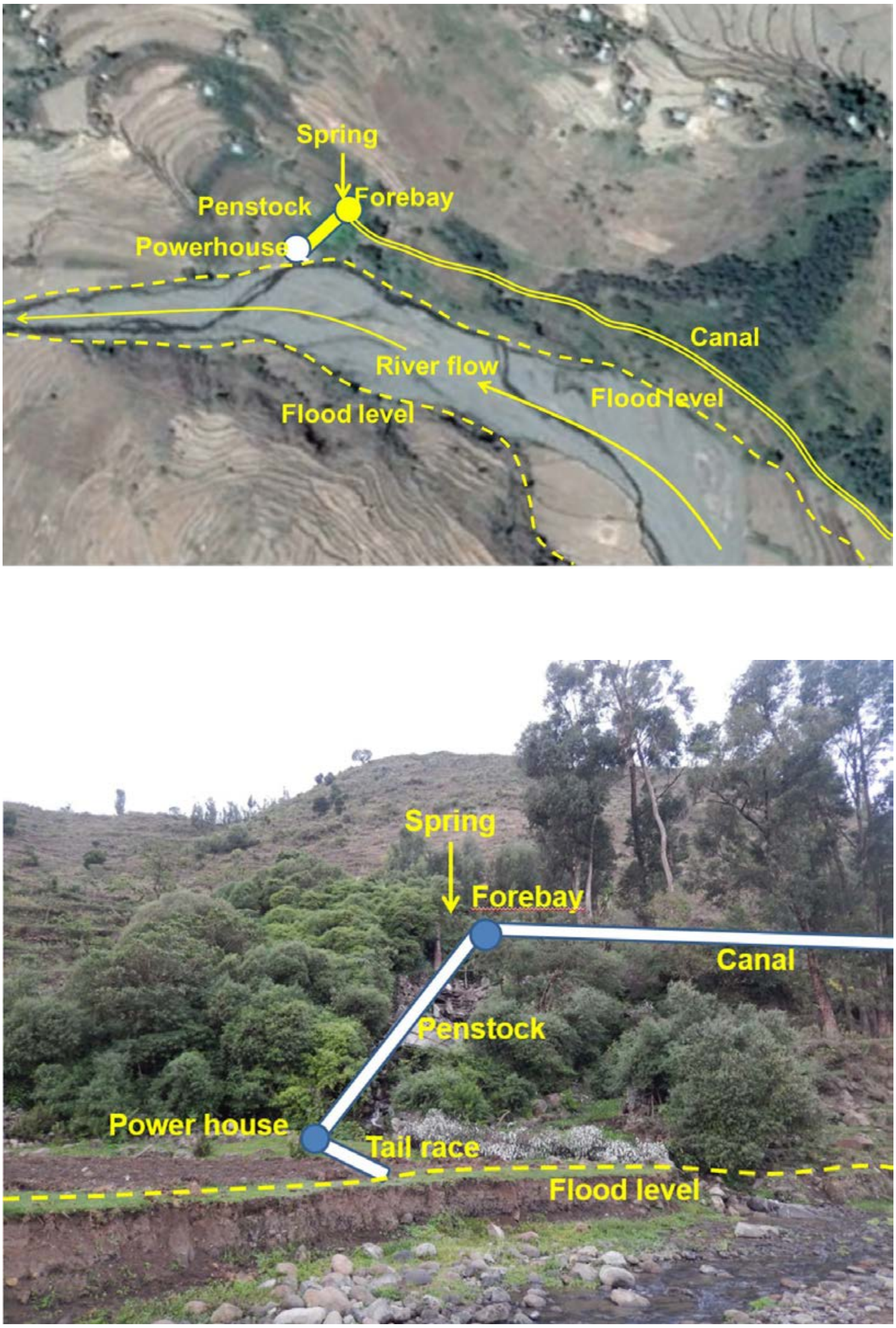



**Figure 18.** Schematic view (above) and panoramic view and penstock (and powerhouse) site (below) of the proposed Gereb MHP site, Amhara r region, Ethiopia.

For the Gereb River, the overall situation of the river and the penstock are shown in Figure 18. The peculiar feature for this site is that a significant amount of the waterflow comes from springs. This is advantageous in comparison to streamflow as springs are expected to be less variable due to climate. The total head for this site as estimated from the theodolite is 25.995 m, which can provide 24.395 m of net head, considering 1.5 m of head loss due to forebay construction. For this site, the FDC could not be calculated as there was no discharge measurement in the area. Estimating the FDC from a hydrological model was also not possible for springs as there was no well-established scientific relationship between the land surface parameters and the spring water volume. During the survey, we measured discharge in March 2018 and the flow value was 0.185 $m^3/s$. Although there was no evident overflow generation, rain did occur and the local conditions were wet and cloudy during the measurement day.

## 5.1.7. Agaro (Naso) MHP site

This is located in Goma woreda, Agaro Zone, Oromia region. It is on the Naso River. The site is densely populated and about 1,000 households reside within a 1.5 km radius (Figure 19). The main income of the people comes from coffee production, with limited maize cultivation. In addition, at this site are two local coffee processing plants, one near the powerhouse and the other near the diversion weir. The power generated would be quite useful for supporting and enhancing small agro-industry – mainly coffee-related business. The local administrative center (kebele center), where public institutions such as an elementary school, clinic, and mosques are located, is less than 1 km from the powerhouse (Figure 20). The nearest electrical grid is about 7 km away.

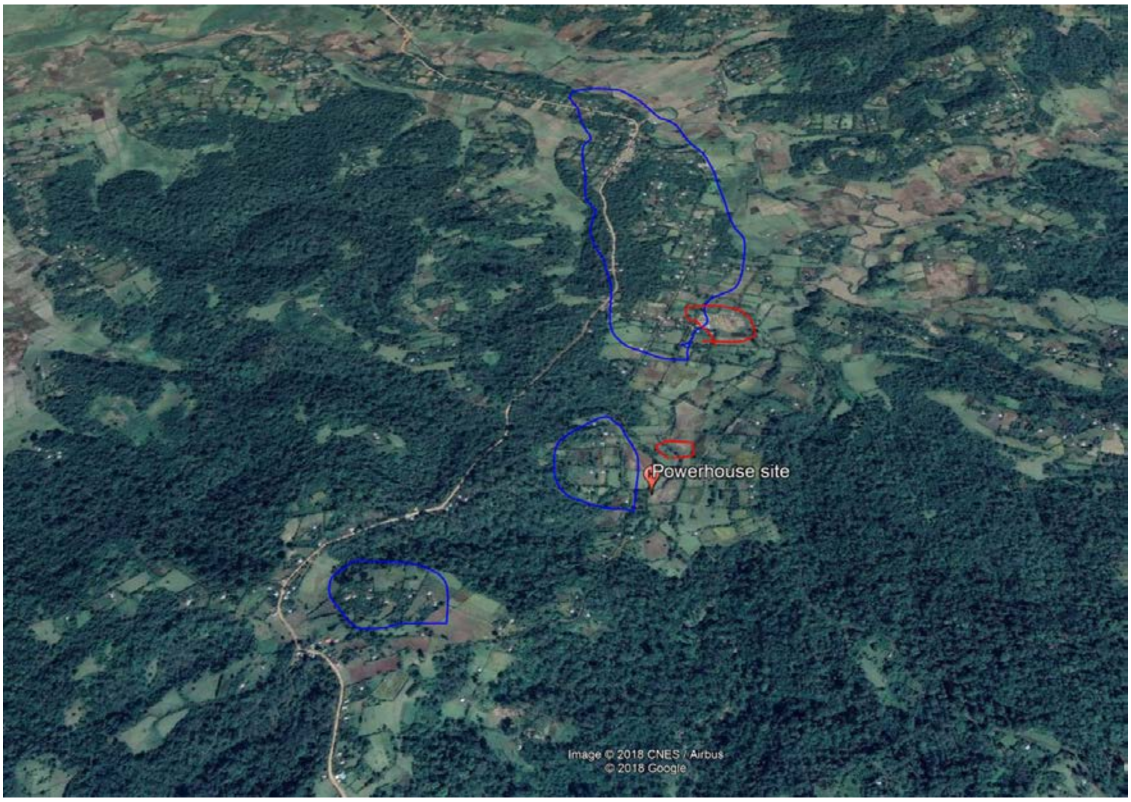



**Figure 19.** Overall site conditions, villages, and institution locations at Agaro MHP site. The large polygon is the kebele center.

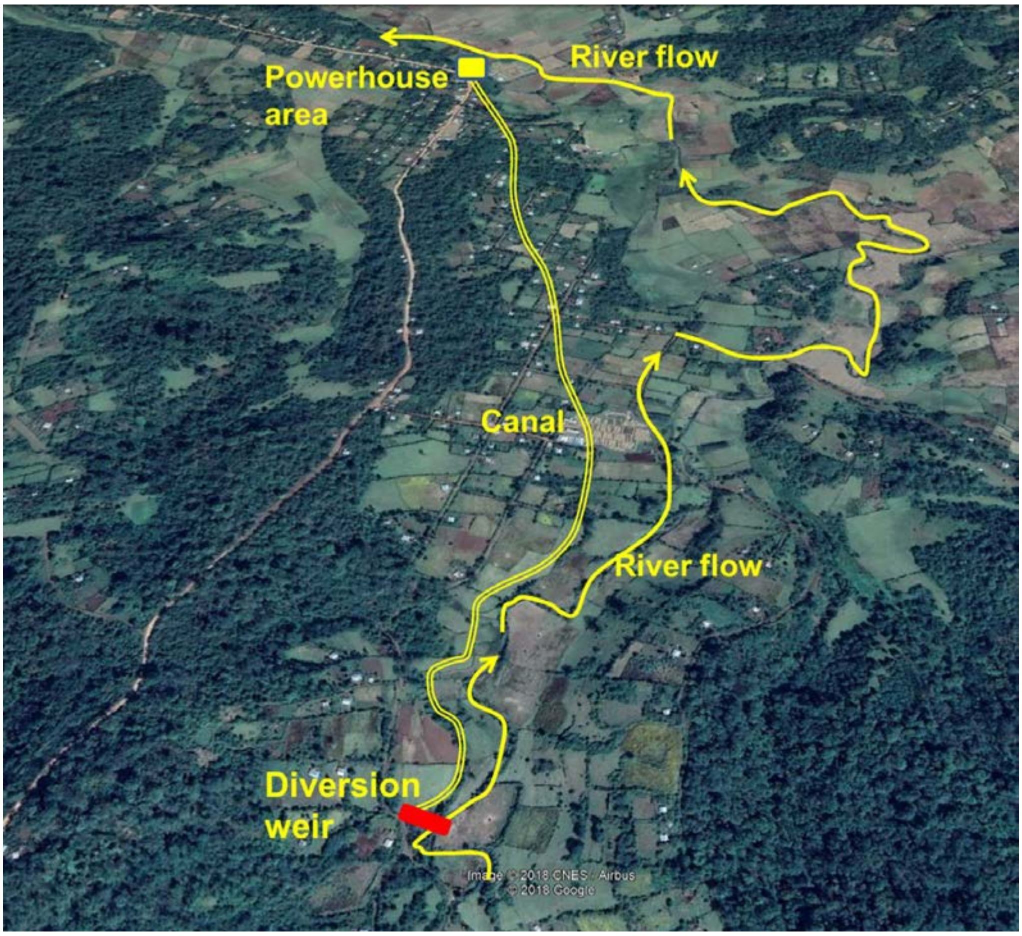




**Figure 20.** Schematic view (above) and panoramic view and penstock (and powerhouse) site (below) of the proposed Agaro MHP site, Oromia region, Ethiopia.

The maximum flow observed was 64.21 $m^3/s$, while the minimum observed in 16 years of simulation was 0.06 $m^3/s$ (Table 7 and Figure 21). The 50th percentile of exceedance was 10.44 $m^3/s$. The observed discharge measured in April 2018 was 0.51 $m^3/s$. The local weather conditions during measurement were wet, with extremely low precipitation. This may not affect the discharge if the climatic conditions are for these specific days.

**Table 7.** Measured and flow duration-based discharge (maximum, minimum, 95th, 90th, 75th, 50th, 25th, 10th, and 5th percentile) of mean daily FDC at Agaro MHP site.

| % | Measured | FDC estimated | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | max | 5 | 10 | 25 | 50 | 75 | 90 | 95 | min |
| Q value | 0.51 | 64.21 | 56.51 | 50.77 | 33.18 | 10.43 | 4.30 | 1.80 | 1.50 | 0.61 |

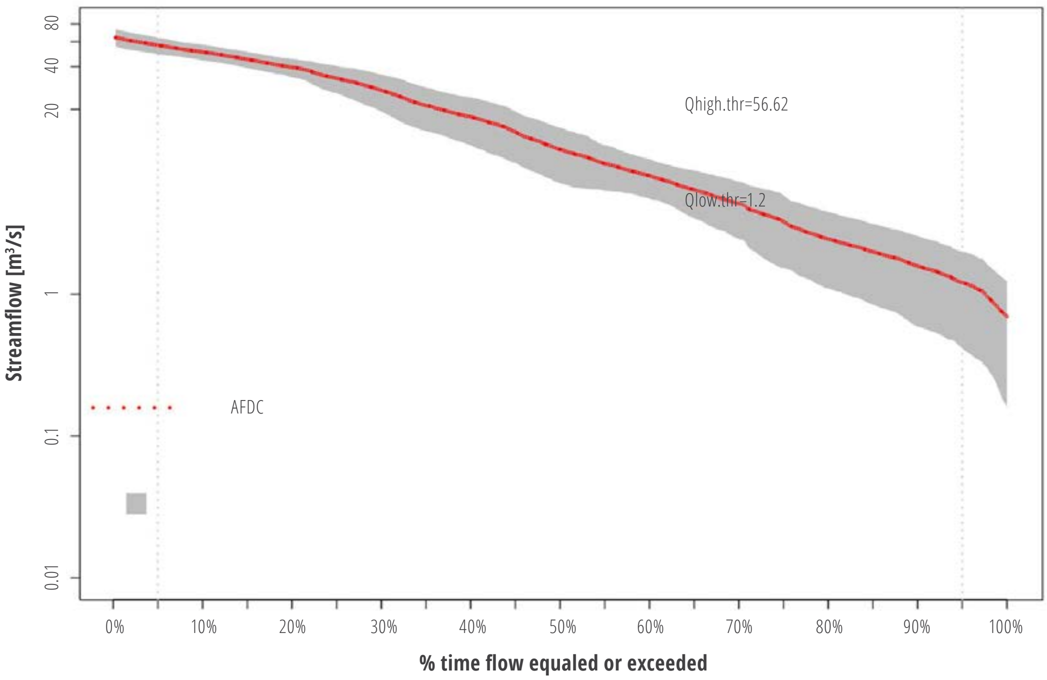
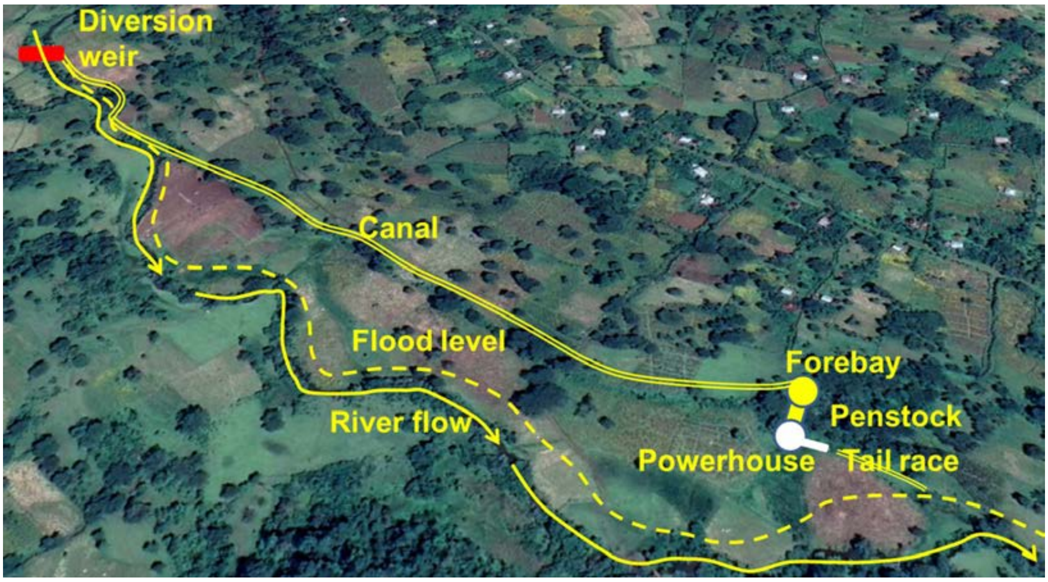



**Figure 21.** Flow duration curve at Agaro site: red line represents the long-term median year while the gray line represents the 95% confidence interval due to annual variability.

## 5.1.8. Elkete Gobe MHP site

This site is located in Seka Chekorsa woreda, Gondi Motoso Zone, Oromia region. The households near the site are estimated to be about 430. As can be seen from Figure 22, the population is evenly and sparsely distributed in the area. The main economic livelihood for the local people is maize, sorghum, coffee, and chat. There are three mosques, one elementary school, and one health center. The nearest electrical grid is in the woreda center (Seka Chekorsa), which is about 15 km from the site.


**Figure 22.** Overall site conditions, villages, and institution locations at Elkete Gobe MHP site. The blue polygon in the image is a small village near the site.



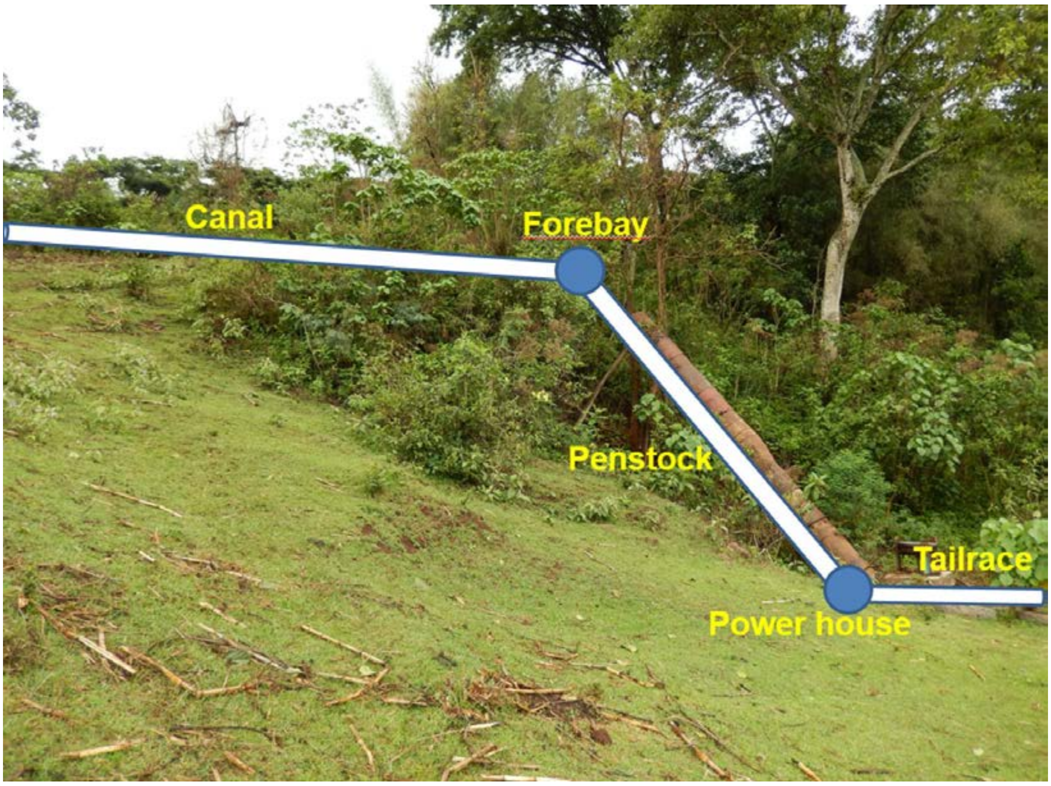




**Figure 23.** Schematic view (above) and panoramic view and penstock (and powerhouse) site (below) of the proposed Elkete Gobe MHP site, Oromia region, Ethiopia.

The diversion weir as it is now is from only Sunki (or Manjor) River, contributory to Gibe River (Figure 23). If diversion from Sunki River is considered, then the flow is relatively smaller, but could be enough for a small plant (Figure 24). With this scenario, the measured discharge in April 2018 was 0.41 $m^3/s$. However, the diversion weir can be established at the main river (Gibe) and the Sunki River could be bridged by canal bridges, thus more than just Sunki's discharge could be obtained. In this case, the discharge measured from the main Gibe River is 0.75 $m^3/s$ (Table 8). The third scenario is to combine the two rivers and increase the discharge much more than each one separately. The total discharge (Sunki plus Gibe) would be 1.16 $m^3/s$. The total head obtained from measurement was 9.71 m. The local weather conditions during measurement were wet and very low intensity precipitation occurred.

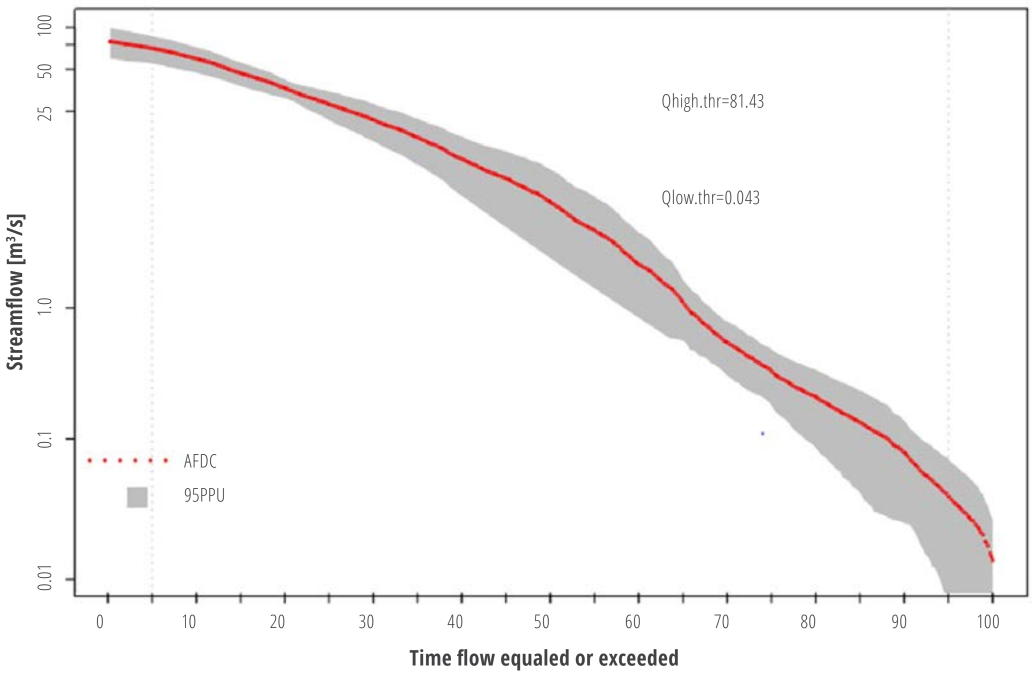



**Figure 24.** Flow duration curve at Elkete Gobe site: red line represents the long-term median year while the gray line represents the 95% confidence interval due to annual variability.

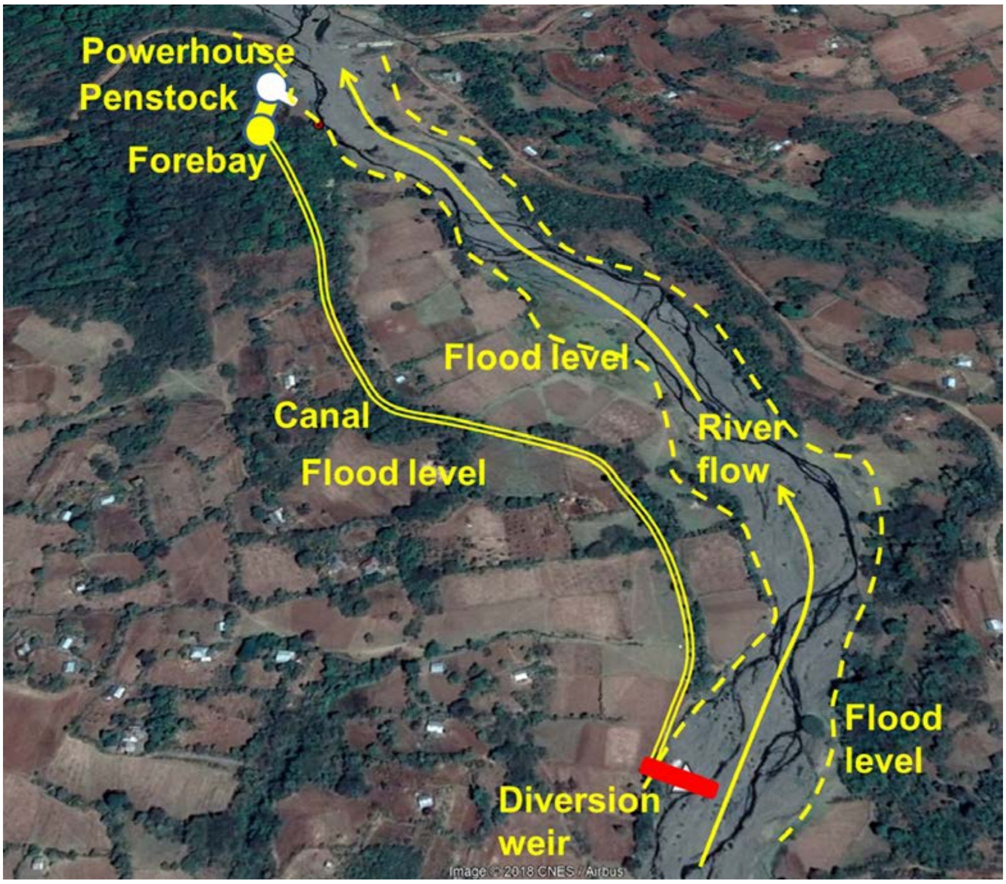
**Table 8.** Measured and flow duration-based discharge (maximum, minimum, 95th, 90th, 75th, 50th, 25th, 10th, and 5th percentile) of mean daily FDC at Elkete Gobe MHP site.

| % | Measured | FDC estimated | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | max | 5 | 10 | 25 | 50 | 75 | 90 | 95 | min |
| Q value | 0.75 | 90.40 | 81.40 | 52.80 | 25.09 | 6.40 | 0.38 | 0.11 | 0.05 | 0.02 |

### 5.1.9. Waro MHP site

The proposed Waro River MHP site is located in Dedo woreda, Oromia region. The total households in the 1.5 km radius are about 500 (Figure 25). The main sources of income are coffee, maize, teff, and potato production. Public institutions (particularly two elementary schools, two mosques, and one health center) exist near the site. The nearest electrical grid access to the site is at Waro kolobe, which is about 7 km from the site. Figure 26 shows a schematic and panoramic view of the site. The maximum head of the penstock (Figure 26) is 22.02 m.


**Figure 25.** Overall site conditions, villages, and institution locations at Waro MHP site. The blue polygon in the image represents small villages near the site.



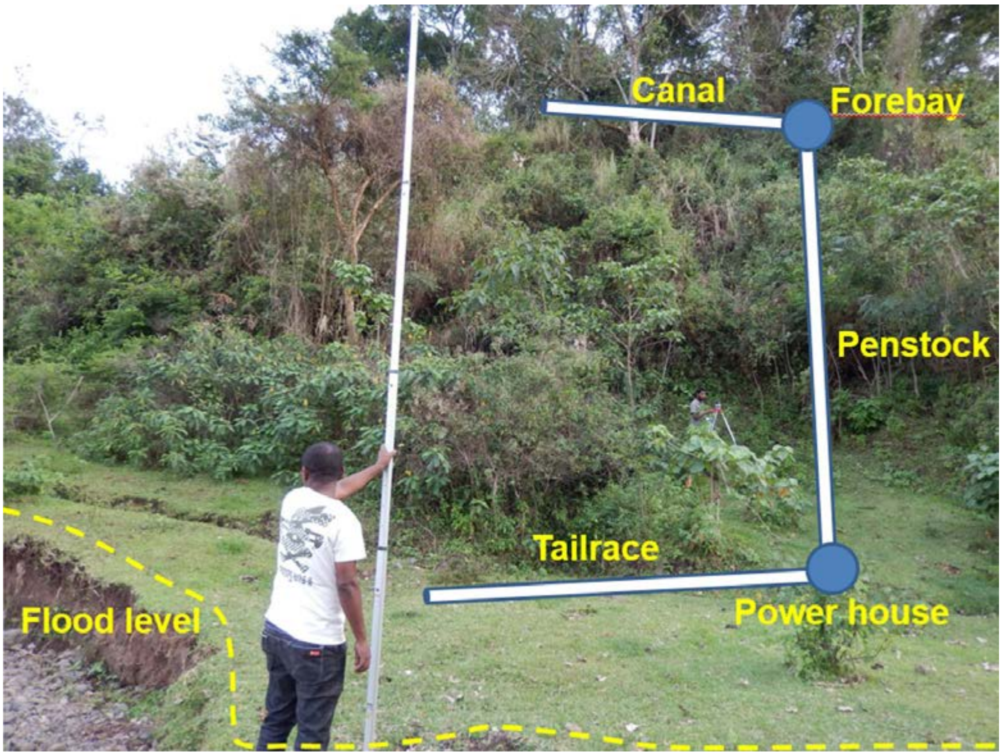




**Figure 26.** Schematic view (above) and panoramic view and penstock (and powerhouse) site (below) of the proposed Waro MHP site, Oromia region, Ethiopia.

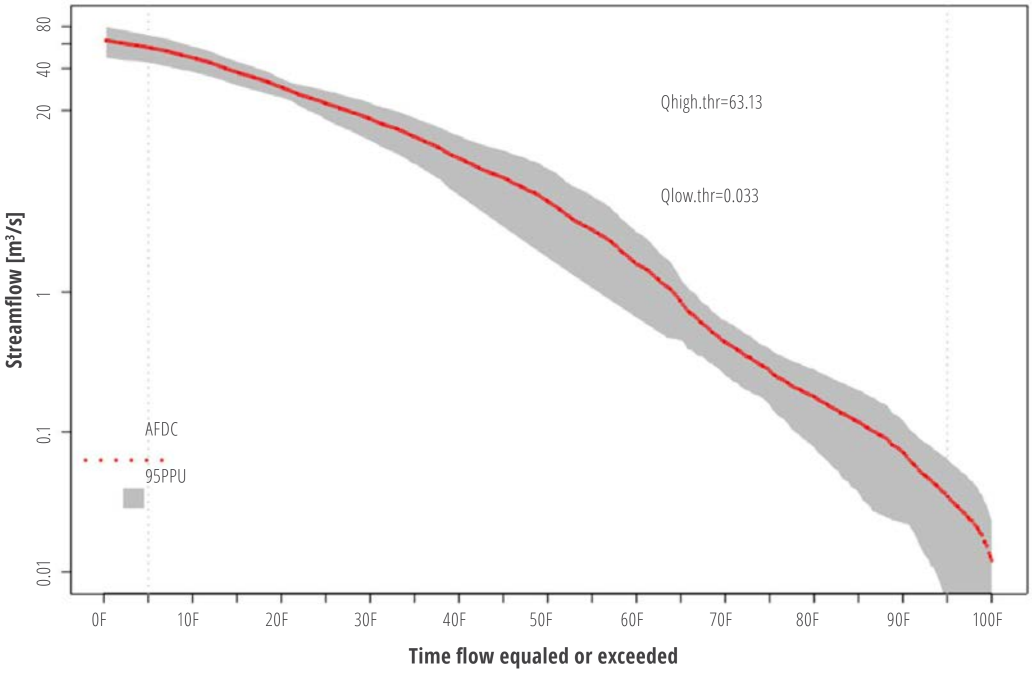



**Figure 27.** Flow duration curve of Waro River at proposed MHP site: red line represents the long-term median year while the gray line represents the 95% confidence interval due to annual variability.

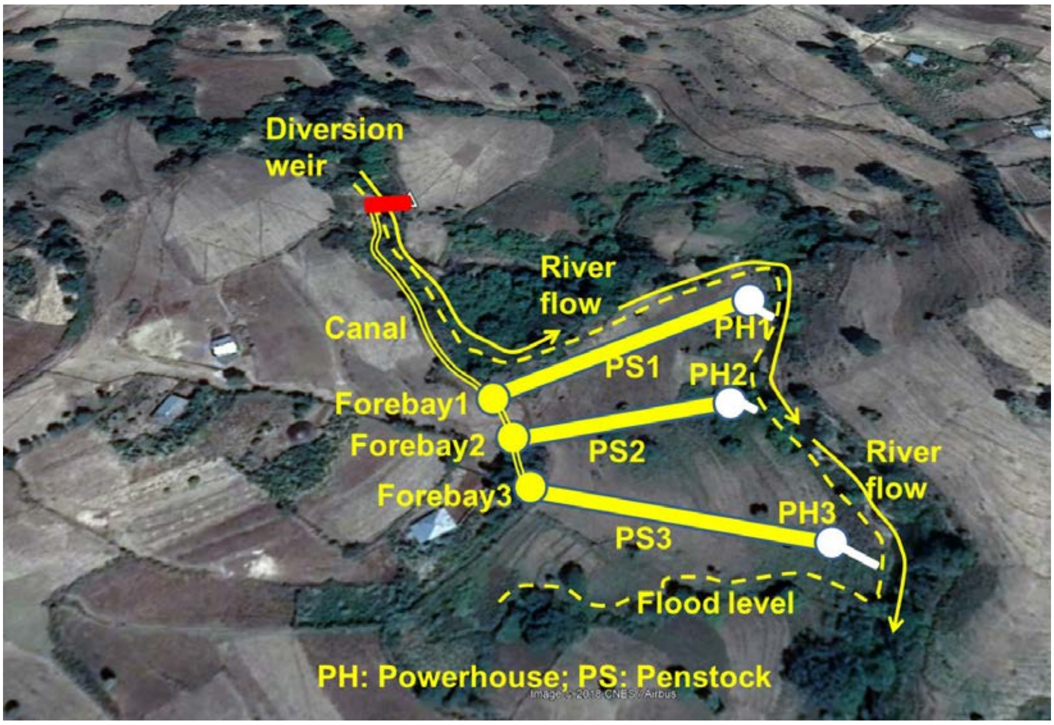
**Table 9.** Measured and flow duration-based discharge (maximum, minimum, 95th, 90th, 75th, 50th, 25th, 10th, and 5th percentile) of mean daily FDC at Waro MHP site.

| % | Measured | FDC estimated | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | max | 5 | 10 | 25 | 50 | 75 | 90 | 95 | min |
| Q value | 0.56 | 70.10 | 63.13 | 41.86 | 19.45 | 4.96 | 0.30 | 0.08 | 0.04 | 0.01 |

The measured discharge in April 2018 was 0.557 $m^3/s$, which does not fall in the lowest flow most likely due to the rainfall week during the field survey week at the site. Detailed statistics and the FDC plot are given in Table 9 and Figure 27, respectively.

## *5.1.10. Omo Beya MHP site*

This is located in Omo Beya woreda, Jimma Zone, Oromia region. The total population living within a 1.5 km radius is 210. Meti and Dura elementary schools and Ocha and Bekene mosques are located within the 1.5 km radius. There is also a health center. The nearest town with an electrical grid is Elke, 7 km from the site.



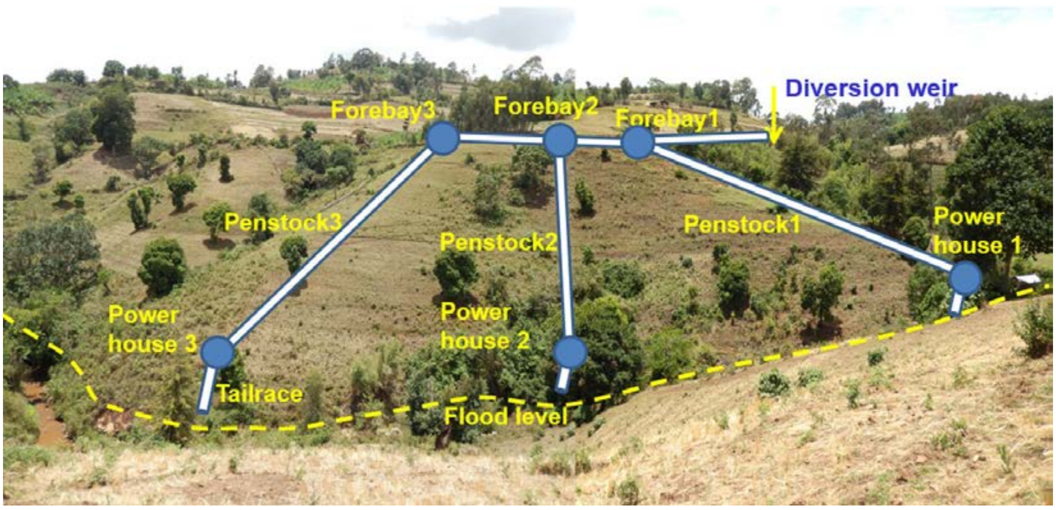




**Figure 28.** Schematic view (above) and panoramic view and penstock (and powerhouse) site (below) of the proposed Waro MHP site, Oromia region, Ethiopia.

Three feasibility penstock options are identified, as depicted in Figure 28, according to the following: (a) Option 1 is along the current mill and it has a relatively gentle slope and lower head (25.69 m) than the others; (b) Option 2 is in a concave topography with higher surface runoff accumulation, with less space for powerhouse construction, a relatively thick soil cover, the penstock requires some support in some parts and more than 1.5 m deep excavation, and it has the lowest head (24.94 m); (c) Option 3 is along a convex topography (with no surface runoff toward the powerhouse) and has a higher head, limited soil thickness for penstock foundation, and suitable powerhouse position (enough space, good foundation, and no flood). We selected Option 3. It has a few meters' increase in canal length and it will have the highest head (36.49 m) and be suitable for workability in both the forebay and powerhouse. Figure 29 shows the flow duration curve and Table 10 shows the discharge at the Omo Beya MHP site.

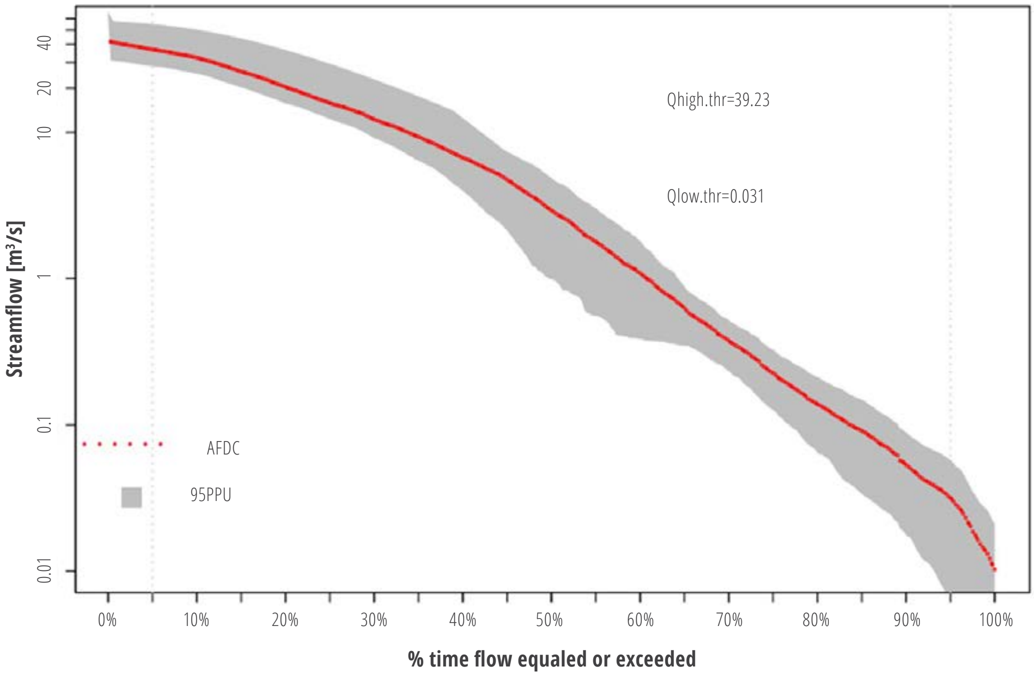


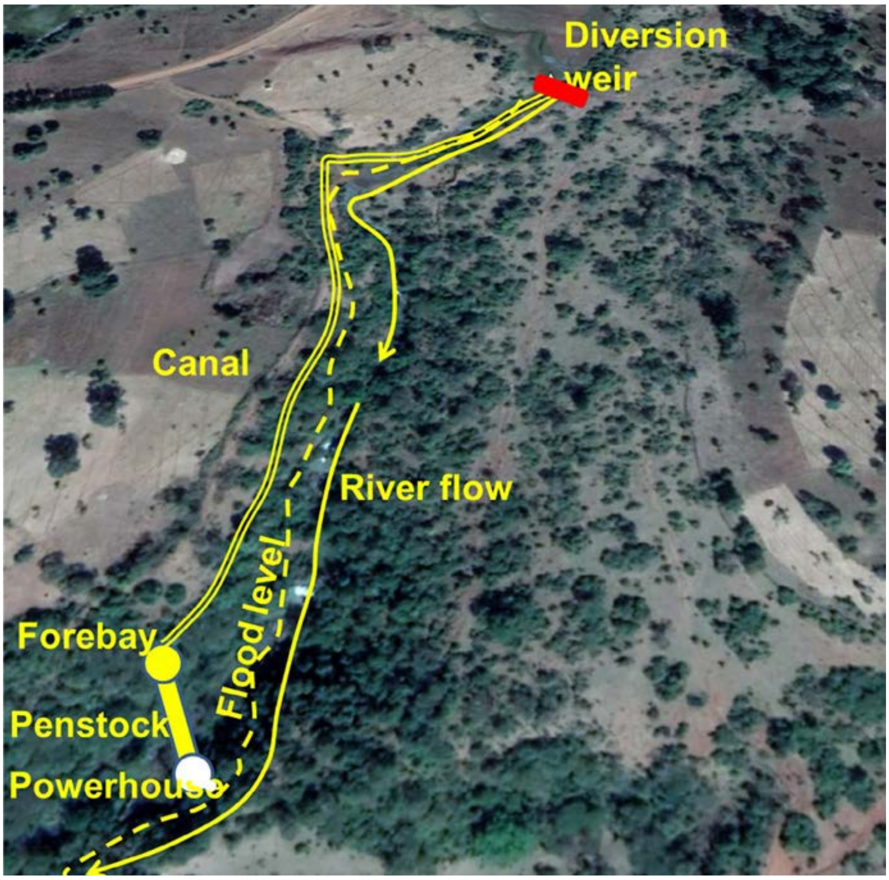

**Figure 29.** Flow duration curve at Omo Beya River at the proposed MHP site: red line represents the long-term median year while the gray line represents the 95% confidence interval due to annual variability.

**Table 10.** Measured and flow duration-based discharge (maximum, minimum, 95th, 90th, 75th, 50th, 25th, 10th, and 5th percentile) of mean daily FDC at the Omo Beya MHP site.

| % | Measured | FDC estimated | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | max | 5 | 10 | 25 | 50 | 75 | 90 | 95 | min |
| Q value | 0.17 | 66.72 | 60.56 | 39.40 | 18.53 | 4.67 | 0.28 | 0.08 | 0.04 | 0.01 |

## *5.1.11. Welege MHP site*

This site is located in Amoro woreda in Oromia region, with a population of 300 households. Agriculture is the mainstay of the economy. The farmers in the vicinity produce teff and maize. Elementary schools and churches also exist. Amoro Town, which is also the woreda's capital, is 2.5 km from the site, which would affect the feasibility of developing an off-grid MHP plant.



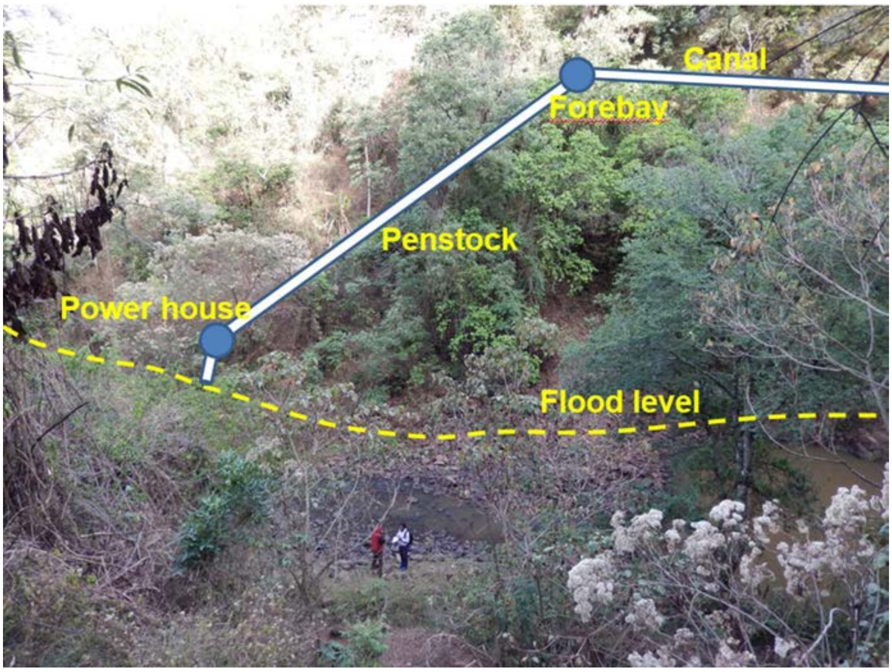




**Figure 30.** Schematic view (above), and panoramic view and penstock (and powerhouse) site (below) of the proposed Welege MHP site, Oromia region, Ethiopia.

Although both sides of the river can be feasible for MHP generation, we identified the right side as the best option due to easy diversion and obtaining higher head. The total head is 27.7 m. The weir position is downstream of a bridge and irrigated land. The weir site is on a narrow area where rock is exposed, with less than 0.5 m of rock at abutments and with bedrock exposed at the river center. Small-scale irrigation is practiced on the upstream side of the proposed weir, which needs further consideration. The powerhouse is located above the flood light, as depicted in Figure 30.

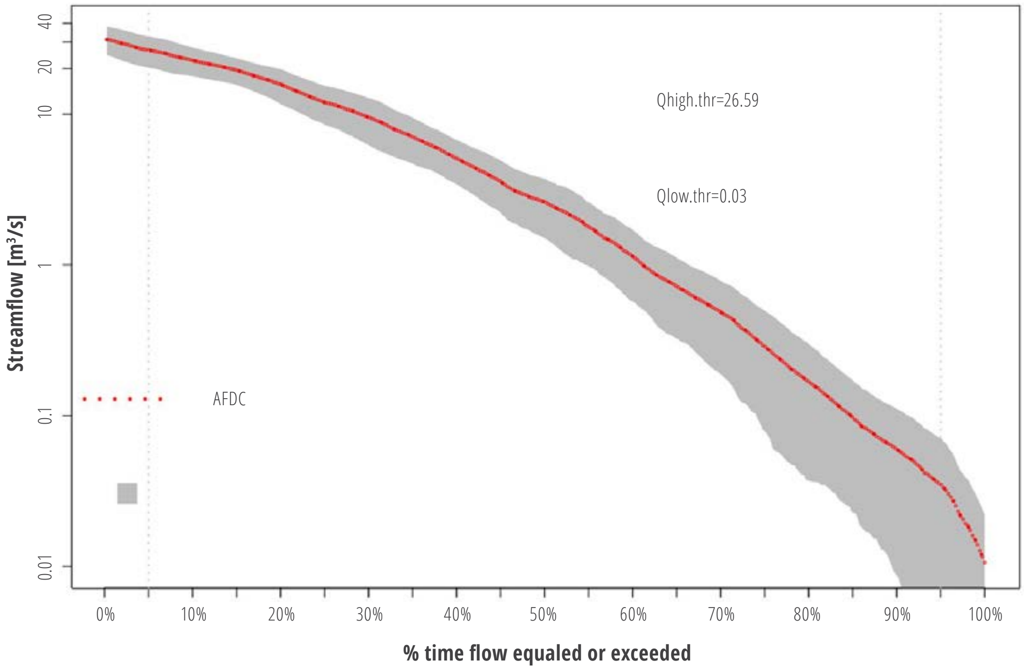



**Figure 31.** Flow duration curve at Welege River at the proposed MHP site: red line represents the long-term median year while the gray line represents the 95% confidence interval due to annual variability.

The FDC for the site is presented in Figure 31 and selected statistics are presented in Table 11. The maximum and minimum flows are 31.34 $m^3/s$ and 0.01 $m^3/s$, while the 50th (median) value is 2.62 $m^3/s$. It is important to note that the discharge recorded in April 2018 was 0.27 $m^3/s$, which lies at 80% of the FDC.

**Table 11.** Measured and flow duration-based discharge (maximum, minimum, 95th, 90th, 75th, 50th, 25th, 10th, and 5th percentile) of mean daily FDC at Welege MHP site.

| % | Measured | FDC estimated | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | max | 5 | 10 | 25 | 50 | 75 | 90 | 95 | min |
| Q value | 0.27 | 31.34 | 26.54 | 22.71 | 11.97 | 2.62 | 0.29 | 0.06 | 0.04 | 0.01 |

## 5.1.12. Gibe MHP site

This site is located in Gudiya Bila woreda in East Wolega Zone, Bila Town (Figure 32). The nearest electrical grid to this site is 8 km away. The rural livelihood in this area is agriculture and there is no additional form of income-generating activities. The main crops are maize, teff, and wheat. Few people have an irrigation project for vegetables and maize. The total households residing within a 1.5 km radius are about 500. In addition are one elementary school, one health center, and one church.

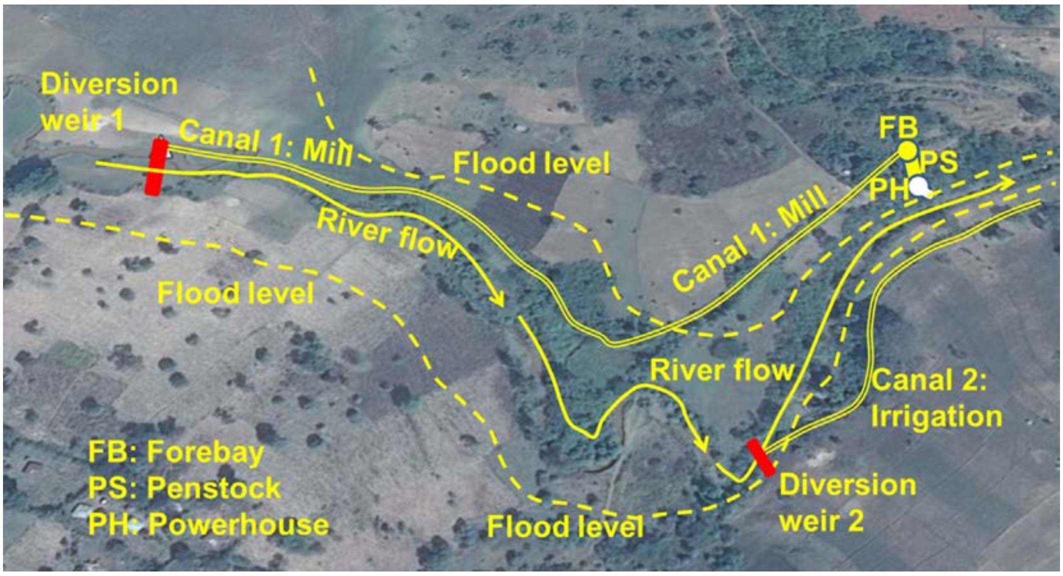




**Figure 32.** Schematic view (above) and panoramic view and penstock (and powerhouse) site (below) of the proposed Gibe MHP site, Oromia region, Ethiopia.

At the weir position, the center of the river is bedrock (basalt) while the river abutment is soil (clayey with depth less than 1.5 m). This site is located on the upper part of the main Gibe River with low variability (as can be seen from Figure 32). The measured discharge, for instance, is one of the highest (1.15 $m^3/s$). On the other hand, the total head is relatively low, with an exact value of 9.9 m. Considering an average of 1.5 m head loss during construction, the net head will be 8.4 m. Figure 33 shows the flow duration curve and Table 12 shows the discharge for the Gibe MHP site.

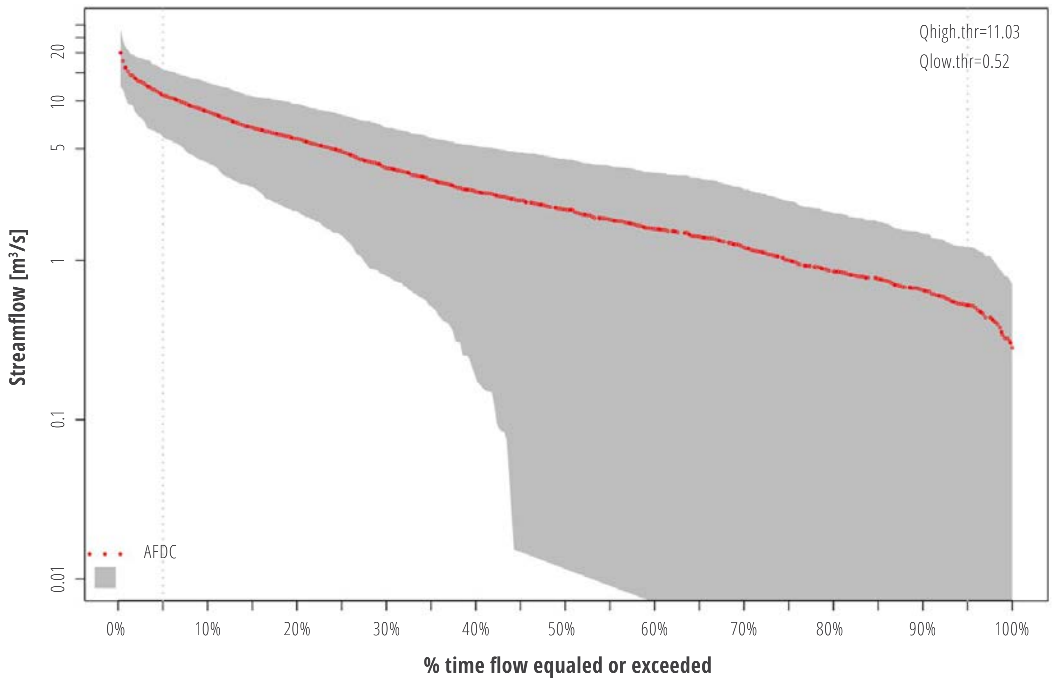



**Figure 33.** Flow duration curve at Gibe River at the proposed MHP site: red line represents the long-term median year while the gray line represents the 95% confidence interval due to annual variability.

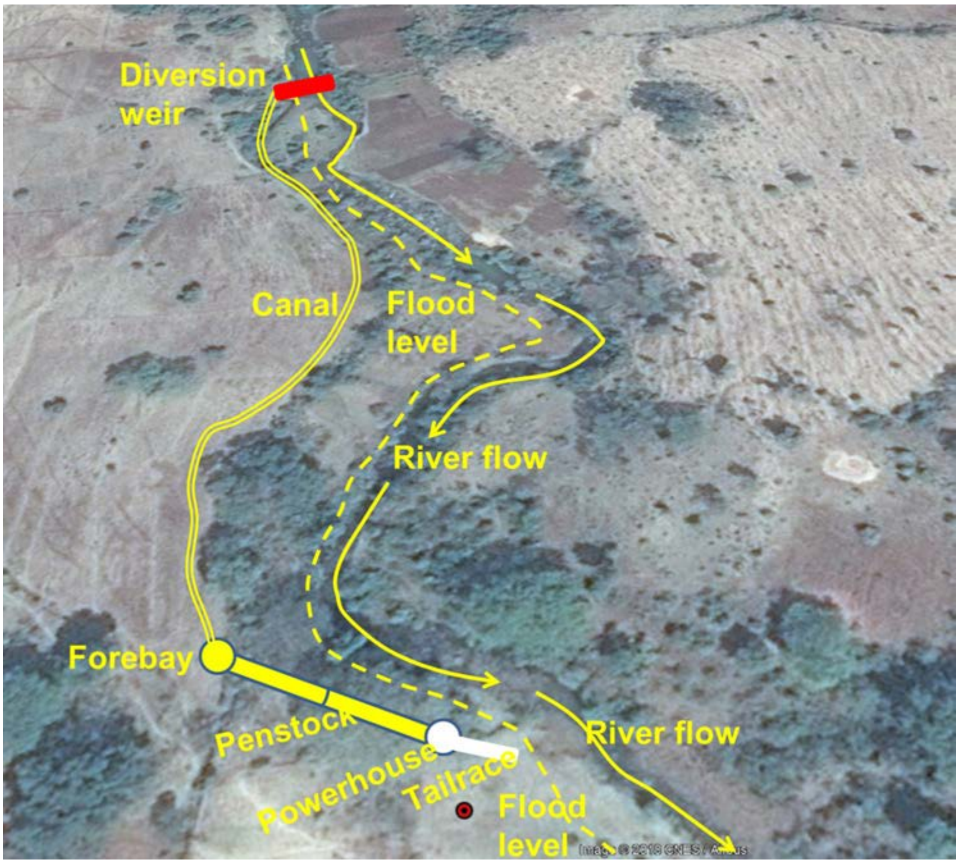
**Table 12.** Measured and flow duration-based discharge (maximum, minimum, 95th, 90th, 75th, 50th, 25th, 10th, and 5th percentile) of mean daily FDC at Gibe River near Baco discharge measurement site.

| % | Measured | FDC estimated | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | max | 5 | 10 | 25 | 50 | 75 | 90 | 95 | min |
| Q value | 1.15 | 22.31 | 10.94 | 8.59 | 4.81 | 2.30 | 1.20 | 0.76 | 0.45 | 0.28 |

### *5.1.13. Idris MHP site*

This is in Sibu Sira woreda in Oromia region. About 170 households reside in a 1.5 km vicinity (Figures 34 and 35). As usual, agriculture, mainly crop cultivation, is the main economic activity in the area. The area has one elementary school, two churches, and one health center. The nearest electricity is in Seri Town, which is about 4.8 km away from this MHP site.


**Figure 34.** Overall site conditions, villages, and institution locations at Idris MHP site. The blue polygons in the image represent small villages near the site.



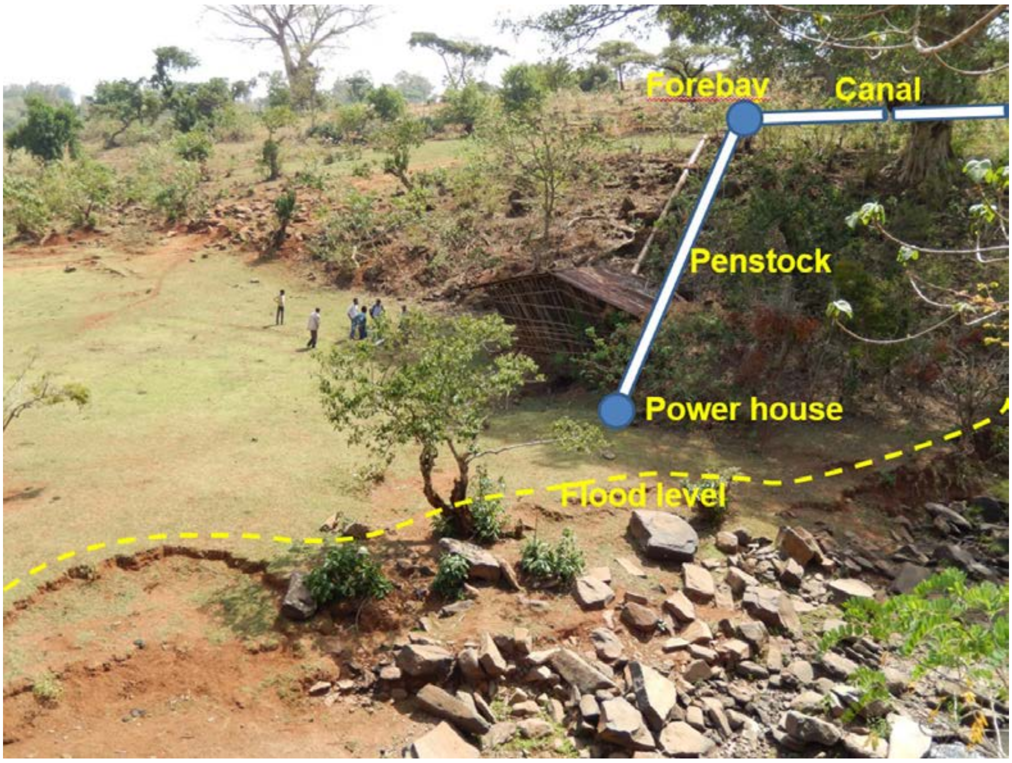



**Figure 35.** Schematic view (above) and panoramic view and penstock (and powerhouse) site (below) of the proposed Idris MHP site, Oromia region, Ethiopia.

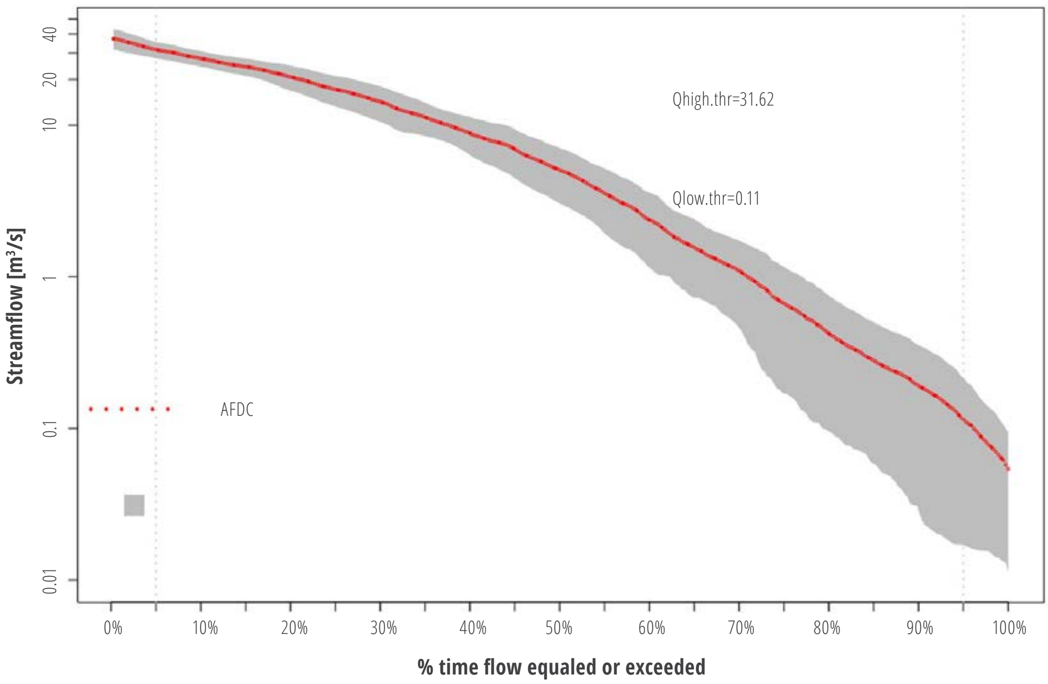



**Figure 36.** Flow duration curve at Idris River at proposed MHP site: red line represents the long-term median year while the gray line represents the 95% confidence interval due to annual variability.

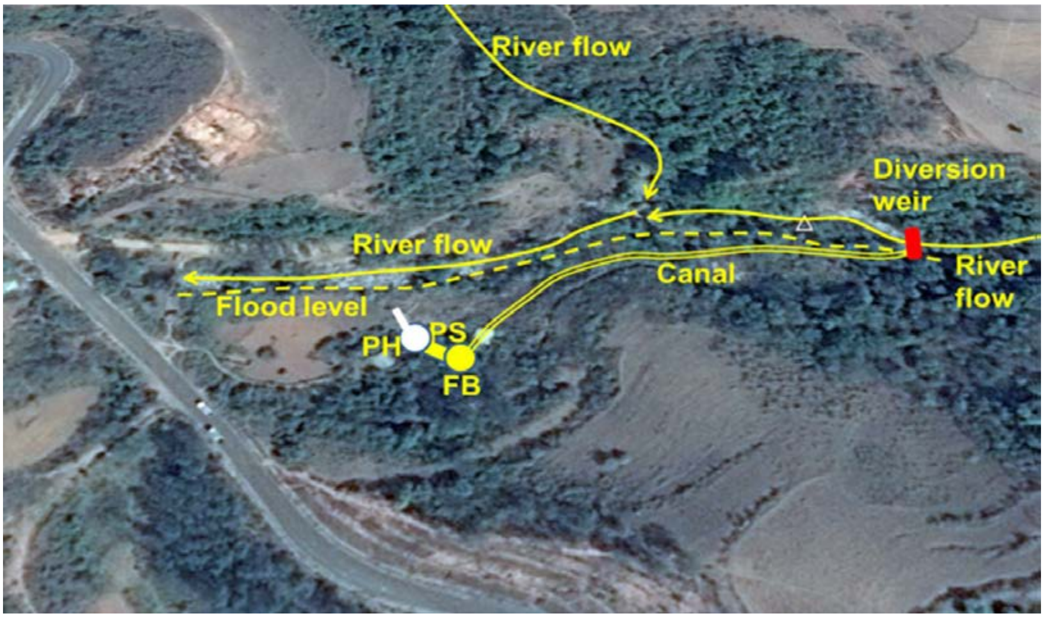
The FDC and some selected statistics for the site are presented in Figure 36 and Table 13, respectively. The measured discharge is 0.34 $m^3/s$, which roughly corresponds to 85% of the FDC curve. The measured flow was recorded during mid-April 2018, which represents low-flow climatic conditions.

**Table 13.** Measured and flow duration-based discharge (maximum, minimum, 95th, 90th, 75th, 50th, 25th, 10th, and 5th percentile) of mean daily FDC at Idris site.

| % | Measured | FDC estimated | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | max | 5 | 10 | 25 | 50 | 75 | 90 | 95 | min |
| Q value | 0.34 | 37.29 | 31.62 | 27.54 | 17.23 | 5.06 | 1.09 | 0.19 | 0.11 | 0.05 |

## *5.1.14. Dilla MHP site*

This site is in Boji Dermiji woreda in West Wellega. An elementary school, Mekaneyesus church, and two health centers are available in the area. The site is precisely on the main asphalt road, making it the most accessible proposed MHP site. Schematic and panoramic views of the site appear in Figure 37 and the flow duration curve appears in Figure 38.



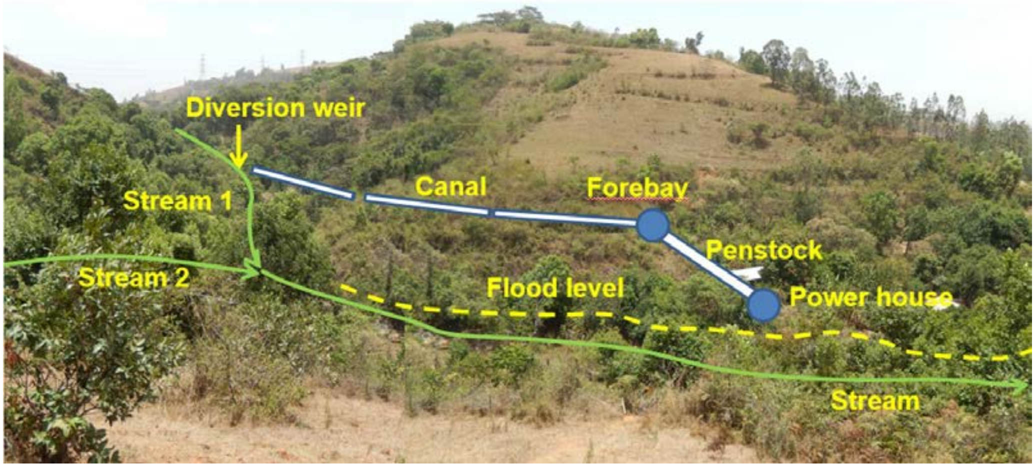



**Figure 37.** Schematic view (above) and panoramic view and penstock (and powerhouse) site (below) of the proposed Dilla MHP site, Oromia region, Ethiopia.

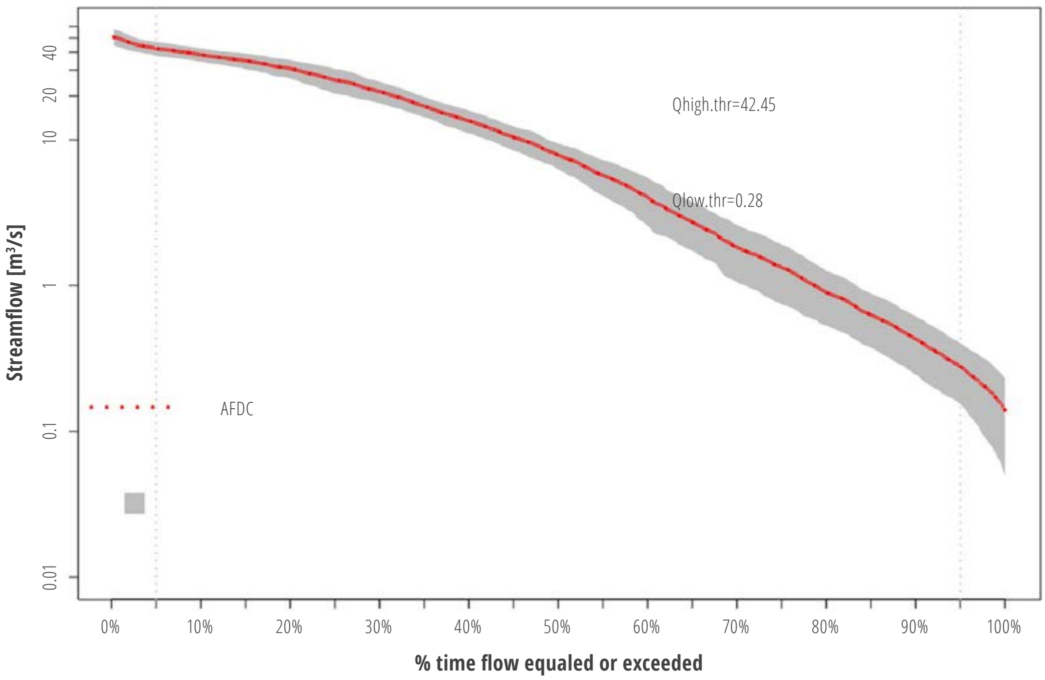



**Figure 38.** Flow duration curve at Dilla River at proposed MHP site: red line represents the long-term median year while the gray line represents the 95% confidence interval due to annual variability.

The discharge volume is one of the largest (1.06 $m^3/s$) as measured in the second week of April 2018. This represents a median value of 870% of the FDC. The other statistics of the site appear in Table 14.

**Table 14.** Measured and flow duration-based discharge (maximum, minimum, 95th, 90th, 75th, 50th, 25th, 10th, and 5th percentile) of mean daily FDC at Dilla site.

| % | Measured | FDC estimated | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | max | 5 | 10 | 25 | 50 | 75 | 90 | 95 | min |
| Q value | 1.06 | 50.51 | 42.36 | 38.32 | 25.66 | 7.87 | 1.33 | 0.43 | 0.28 | 0.14 |

## 5.1.15. Barudemeti MHP site

For this site, the net head is 2.87 m, which gives it the shortest head from the 15 proposed sites (Figure 39). Thus, hydrological FDC was not estimated for it. The measured discharge in the second week of April 2018 was 0.31 $m^3/s$.


**Figure 39.** Panoramic view and penstock (and powerhouse) site of the proposed Barudemeti MHP site, Oromia region, Ethiopia.

## 5.2. Estimated hydropower at each MHP site

Based on the flow duration curve and natural drop of the river profile (i.e., head) and the site-specific suitability of the powerhouse location, we estimated the theoretical power generating capacity of each site (Figure 40). Instead of providing a single value of power generation, we provided the power generation for all the flow duration curve throughout the year. Overall, the 15 sites can generate greater than or equal to 2,286 kW of power during 75% of the time, 11,640 kW during 50% of the time, and 51,072 kW during 25% of the time of the year.

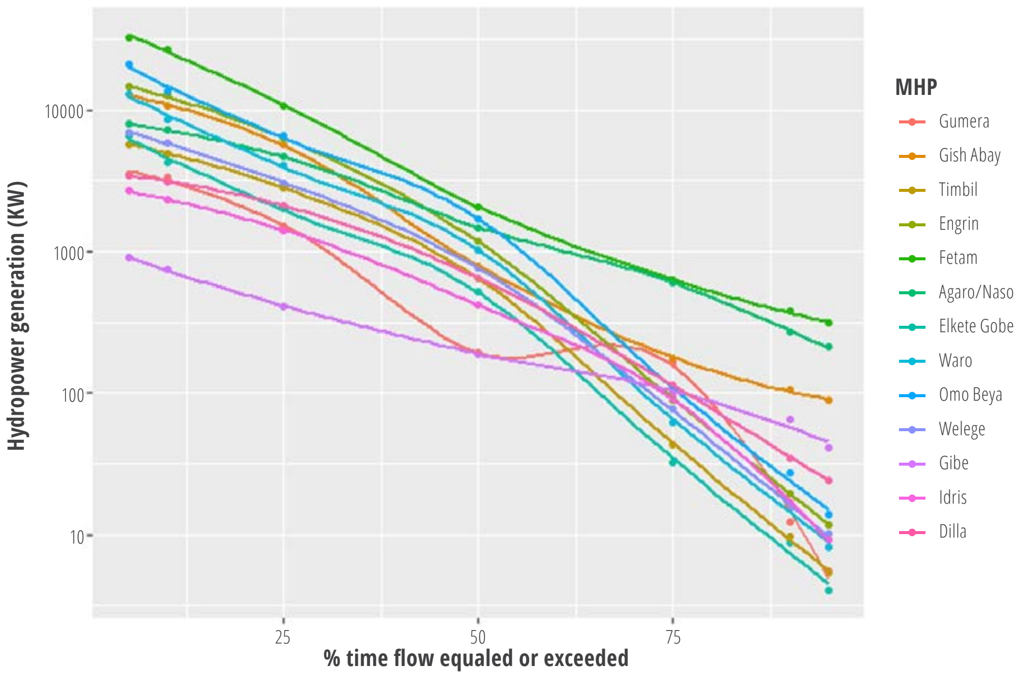



**Figure 40.** Estimated hydropower generation for different levels of flow for all the MHP sites.

CIAT/Wuletawu Abera

# 6. Conclusions and future research

The coupled opportunity of availability flow throughout the year and a series of cataracts along most of the river profiles in the highlands of Ethiopia provide a great opportunity to improve energy penetration using hydropower of varied capacity in the rural areas of Ethiopia. Here, we conducted a technical feasibility study of 15 selected sites in the highlands of the country for mini-hydropower generation. At all sites, hydropower generation can reach 11,640 kW half of the time of the year, and as low as 2,286 kW on a few dry days of the year. Based on this exercise, we recommend the following for future research directions:

- We conducted a feasibility study for selected sites, but it is important to develop an approach that is useful to assess MHP potential in a spatially continuous manner to assess the national potential of MHP.

- MHP primarily depends on rainfall availability; therefore, the impact of global climate change on hydroelectric power generation should be integrated as part of assessing MHP potential.

- Complementary renewable energy such as solar, wind, and geothermal is a key for improving the penetration rate of renewable energy in the country. Climate-based RE sources could have a complementary nature in terms of both temporal and spatial context. During the summer season, hydropower can be the main source of power. During winter, solar can be the main source of power. During autumn and spring, power generated by wind could be used more than the others.

- Spatially, the highland areas of the country such as Tekeze basin, Upper Blue Nile basin, Omo-Gibe basin, and some areas in Arsi highlands are the sources of hydropower, whereas the lowlands such as Afar, Somalia, and many others could be a good source of solar power. The mountain escarpment along the North Shao to Tigray could become a tower of windmills.

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# Appendix

**Table A1.** Overall geotechnical conditions of all 15 MHP sites.

| No. | Site name | Diversion weir | Canal route | Forebay area | Penstock route/ area | Powerhouse and tail race area | Water use |
|---|---|---|---|---|---|---|---|
| 1 | Gumera | Good foundation with depth of bedrock not exceeding 1 m at center of the river and 1.5 m at abutments. No slope stability problem. | Short length and passes through flat area. The soil/ weathered rock along the route is pervious. | Fractured rock, which requires excavation and lining. | Shallow soil (less than 0.5 m in depth) and weathered rock, no slope stability problem. | Good foundation with soil thickness less than 1.5 m (weathered rock), no slope stability problem and enough space for powerhouse and tailrace. | No competition for water use in the upstream area. Small-scale irrigation downstream of the MHP sites could still use the released water. |
| 2 | Geshe Abay | Hard rock (basalt), which requires proper keying to the stratum at center and abutments. No slope stability problem. | The canal route (left and right) passes through stable rock, which requires excavation. The rock is fractured and pervious at shallow depth. | Forebay at right side of river: on relatively flat area with enough space for storage, and with no slope stability problem. | Shallow soil (less than 0.5 m in depth) and weathered rock, no slope stability problem. | Good foundation with debris/soil materials not exceeding 1.5 m thick and weathered rock. No slope stability problem and enough space for powerhouse and tailrace. | No competition for water use in the upstream or downstream area. |
| | | | | Forebay at left side of the river: on steep area with limited space for storage. Creeping and rock block instability observed. | Loose soil with depth not less than 1 m and with signs of slope instability (creep) and hanging rock blocks along the penstock route. The topography of the route requires support for the penstock. | The foundation area is on thick soil (not less than 2 m in thickness). No slope stability problem and enough space for powerhouse and tailrace. | |
| 3 | Timbil | Weathered rock (basalt) at river center and soil depth not more than 1 m at abutments. No slope stability problem. | The right canal route passes through stable terrain but requires more cut. The rock is fractured and pervious at shallow depth, which requires lining. | The forebay at right and left side is on a relatively flat area with enough space for storage, and with no slope stability problem. | The penstock area on both left and right side has shallow soil depth (not more than 1 m) and has no slope stability problem. | Good foundation with soil depth not exceeding about 1 m. No slope stability problem and enough space for powerhouse and tailrace. | No competition for water uses in the upstream or downstream area. |
| | | | The left canal route passes through stable terrain and requires less cut. The rock is fractured and pervious at shallow depth, which requires lining. | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **4** | Engrin | Weathered rock (basalt) at river center and soil depth not more than 0.5 m at abutments. No slope stability problem. | The canal route crosses small creeks and passes at the foot of a sloping area: siltation of canal is expected in case of open canal. The soil/weathered rock along the route is pervious. | The forebay area is on relatively flat terrain with enough space for storage, and with no slope stability problem. | The penstock route is associated with debris/boulder materials: it needs clearing of boulders and debris materials. No signs of slope instability were observed. | Good foundation with soil depth not exceeding about 1.5 m. No slope stability problem observed and enough space for powerhouse and tailrace. | No competition for water use in the upstream area. |
| **5** | Fetam | Soil cover along the diversion weir axis: estimated soil depth more than 2 m. Weir should be placed in good foundation and keyed to stable stratum. No slope stability problem at weir site. | The canal route passes through a flat terrain with pervious soil/weathered rock. | The Forebay area is on relatively flat terrain with very good site for storage, and with no slope stability problem. | The penstock route passes through variable soil/ rock masses: soil, boulders, and weathered rock. The debris/boulder materials are associated with some slope instability: boulders and debris materials need to be removed, and penstock should be founded on stable stratum. | Good foundation with soil depth not exceeding about 1 m. No slope stability problem observed and there is enough space for powerhouse and tailrace. | No competition for water use in the upstream area. The planned small-scale irrigation downstream of the MHP could be integrated for optimized development. |
| **6** | Gereb | Alluvial soils are at the river center and terrace deposits at abutments. No slope stability at weir site but the river is relatively wide in the flood plain. | The canal route passes through soil/ weathered rock and along the foot of a hilly area: siltation is a challenge if an open canal is used. | The forebay area is close to a spring, which is contributing to the water source. Boulders and debris deposits dominate the site, which requires further study for forebay design. | The penstock route passes through boulders/debris materials and weathered rock. These boulders and debris materials need to be removed, and the penstock should be found on stable stratum. | Good foundation with soil depth not exceeding about 1.5 m. No slope stability problem observed and there is enough space for powerhouse and tailrace. | The spring water in the area is used for small-scale irrigation and for drinking (livestock and humans). There is a need to integrate MHP development and use of the released water from the tailrace for irrigation in the area. |
| **7** | Agaro/Naso | Weathered rock (basalt) at river center and soil depth not more than 1 m at abutments. The left side of the abutment is very stiff, which requires further stability evaluation during detailed design. | The canal route is relatively long and passes mainly through pervious soil and weathered rock with several crossings/drainage lines. Potential siltation and seepage problems of the canal route require consideration during design. | Forebay area is on gentle slope terrain with enough space for storage, and with no slope stability problem. | The penstock area has shallow soil depth (not more than 0.5 m) and has no slope stability problem. | Good foundation with soil thickness less than 1 m (weathered rock), no slope stability problem, and enough space for powerhouse and tailrace. | No competition for water use in the upstream area. |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **8** | Elkete Gobe | Alluvial soil (depth up to 1 m) at river center and soil depth not less than 1.5 m at abutments. | The canal route is relatively long; passes through foot of a hilly area and crosses several drainage lines. The soil/rock along the canal route is pervious. Siltation and seepage problems of canal route require consideration during design. | Forebay area has limited area for storage but there is no slope stability problem. | Loose soil with depth not less than 1.5 m and with signs of slope instability (creep) along the penstock route. The topography of the route requires support for the penstock. | Foundation area is on thick soil (not less than 2 m in thickness) but there is enough space for powerhouse and tailrace. | No competition for water use in the upstream area. |
| **9** | Waro | Alluvial soil (depth not less than 8 m) at river center and soil (alluvial and sand/silt) at abutments. The river is very wide, which requires design of special types of diversion, which requires annual maintenance. | The canal route passes through soil/weathered rock that is pervious. No slope stability problem along the route. | Forebay area has limited area for storage but there is no slope stability problem. | Soil with depth not less than 2 m but with no sign of slope instability. | Foundation area is on soil (thickness not less than 2 m) but there is enough space for powerhouse and tailrace. | No competition for water use in the upstream area. |
| **10** | Omo Beya | Weathered rock (basalt) at river center and soil depth not more than 1 m at abutments. No slope stability problem. | The canal route is relatively short and passes through weathered rock that is pervious. No slope stability problem along the route. | Forebay area (for the three sites) is on relatively flat terrain with enough space for storage, and with no slope stability problem. | Option 1: Passes through existing mill with soil depth less than 1 m and weathered rock. No slope stability problem. | Option 1: Foundation area is on soil (thickness not more than 1 m) but there is enough space for powerhouse and tailrace. | No competition for water use in the upstream area. |
| | | | | | Option 2: Passes through soil (depth less than 1 m) and weathered rock. No slope stability problem. | Option 2: Foundation area is on soil (thickness not more than 1 m) but there is enough space for powerhouse and tailrace. | |
| | | | | | Option 3: Passes through soil (depth less than 1 m) and weathered rock. No slope stability problem. | Option 3: Foundation area is on soil (thickness not more than 1 m) but there is enough space for powerhouse and tailrace. | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **11** | Welege | Weathered rock (basalt) at river center and soil depth not more than 0.5 m at right abutment and rock at left abutment. No slope stability problem. | The canal route is relatively short and passes through weathered rock that is pervious. No slope stability problem along the route. | Forebay area is on relatively steep area with limited space for storage, and with no slope stability problem. | The penstock area has soil depth not more than 1 m and has no slope stability problem. | Foundation area is soil (thickness not more than 1 m) with limited space for powerhouse and tailrace. | There is small-scale irrigation upstream of the diversion weir area, which requires further evaluation of its impact on water demand. |
| **12** | Gibe | The site is on a relatively flat and flood plain area with wide valley. The foundation area is soil at abutments and weathered rock at the center of the river. Flooding is a major problem. | The canal route passes through soil and weathered rock that is pervious. No slope stability problem along the route. | Forebay area is on relatively gentle area with enough space for storage, and with no slope stability problem. | The penstock area has boulders and soil depth less than 2 m. No slope stability problem along the route. | Foundation area is boulders and soil (thickness not less than 1.5 m) and with limited space for powerhouse and tailrace. | There is small-scale irrigation downstream of the diversion weir area. |
| **13** | Idris | Weathered rock (basalt) at river center and soil depth not more than 1.5 m at abutments. No slope stability problem. | The canal route passes through soil and weathered rock that is pervious. No slope stability problem along the route. | Forebay area is on relatively gentle area with enough space or storage, and with no slope stability problem. | The penstock area has boulders and soil depth less than 2 m. No slope stability problem along the route. | Foundation area is boulders and soil (thickness not less than 1.5 m) and with enough space for powerhouse and tailrace. | No competition for water use in the upstream area. |
| **14** | Dilla | The site is associated with boulders and weathered rock (basalt). | The canal route passes through the foot of a hilly area and soil/weathered rock along the route is pervious. The existing irrigation canal is affected by siltation, seepage, and landslides, which requires consideration in the design of MHP. | Forebay area is on relatively gentle area with enough space for storage, and with no slope stability problem. | The penstock area has soil depth not more than 1.5 m and has no slope stability problem. | Foundation area is soil (thickness not more than 1 m) with enough space for powerhouse and tailrace. | There is irrigation practice downstream of the diversion weir. There is also irrigation downstream of the powerhouse area. Water released from the tailrace could be used for irrigation purposes. |
| **15** | Barudemeti | The site is on a relatively flat and flood plain area with wide stream. The foundation area is waterlogged. Flooding is a major problem. | The canal route passes through soil that is pervious. The route is waterlogged. No slope stability problem along the route. | Forebay area is on relatively gentle area with enough space for storage, and with no slope stability problem. | The penstock area has soil depth not more than 1.5 m and has no slope stability problem. | Foundation area is soil (thickness not less than 2 m) and with enough space for powerhouse and tailrace. | No competition for water use in the upstream area. |

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