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Research Article

Prioritization Suitable Hydropower Potential Sites Along the Furfuro River, Ethiopia

Amsayaw Genet[1,*], Abebe Tadesse[2], Temesgen Zelalem[1], Tensay Kifle[3], Aynadis Ejargew[4]

[1]Department of Hydraulic Engineering, College of Engineering and Technology, Wolkite University, Wolkite, Ethiopia
[2]Department of Hydraulic Engineering, Institute of Technology, Hawassa University, Hawassa, Ethiopia
[3]Department of Water Supply and Environmental Engineering, College of Engineering and Technology, Werabe University, Werabe, Ethiopia
[4]Department of Water Resource and Irrigation Engineering, College of Engineering and Technology, Dilla University, Dilla, Ethiopia

Abstract

Energy access is a critical factor for economic development and social progress, particularly in rural areas of developing countries like Ethiopia. This study aims to identify and prioritize suitable hydropower sites along the Furfuro River using a multi-criteria decision analysis (MCDA) approach, specifically the analytic hierarchy process (AHP). Five key criteria were considered: power, discharge, head, accessibility, and distance. A pairwise comparison matrix was constructed to assess the relative importance of these criteria. Normalization and critical weight calculation were performed to determine the weight of each criterion. The consistency of the pairwise comparison matrix was evaluated using the consistency ratio (CR), which was found to be acceptable. The site with the highest suitability index was ranked the most suitable for hydropower development. The findings of this study provide valuable insights for decision-makers in prioritizing hydropower development in the region, reducing reliance on traditional, harmful energy sources, and improving the quality of life for local communities along the Furfuro River. By considering multiple factors and employing the Analytic Hierarchy Process, this research contributes to sustainable energy planning and resource management.

Keywords

Analytic Hierarchy Process, Furfuro River, Potential Site, Prioritized Sites, Suitability Index

1. Introduction

Hydropower is an important green energy source; it generates around 16% of the world's electricity. Water movement can produce energy in the form of hydropower. The snow or rain that creates streams and rivers comes from mountains or hills. The earliest hydroelectric power plants were constructed at Niagara Falls in 1879; the falls began using hydropower in 1881; in 1882, along the Fox River, close to Appleton, Wisconsin, the world's first hydroelectric plant started producing

*Corresponding author: amsayawgenet@gmail.com (Amsayaw Genet)

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electricity. Hydropower first generated energy in the late 19th century [1]. It derives from water that is flowing downhill a river's course, either from rivers or streams, due to the force of gravity. The kinetic energy that is linked to this flowing water is released due to the friction between the water and the rocks and silt in the riverbeds [2].

Only the Democratic Republic of the Congo has a larger hydroelectric potential in Africa than Ethiopia, with a potential capacity of up to 45,000 MW (MoWE, 2017) [3]. With a 6.6 MW installed capacity, the first Aba Samuel dam was ordered in 1932 and represented the start of the hydropower operation [4]. Ethiopia's topography has potential for hydropower development. Ethiopia is referred to as the Water Tower of North Eastern Africa because it has ten river basins, of which the Omo, Wabi Shebelle, Genale-Dawa, Blue Nile, and Omo are international rivers, as well as hundreds of streams that feed into the main rivers, which pass through its hilly terrain in all directions. Additionally, each river basin gets enough rainfall to cover sizable catchment areas. Considering that 86 percent of the waters of the Blue Nile originate in Ethiopia [5].

Multi-criteria decision-making (MCDM) is a fundamental issue in decision-making since it looks at several elements during the selection process in an attempt to determine the best alternative [6]. Multi-criteria analysis (MCA) is a powerful tool for decision-making in environmental management, including renewable energy planning and hydropower potential site selection. MCA is a structured framework for evaluating and ranking different alternatives based on multiple, often conflicting criteria. It's a powerful tool for hydropower potential assessment, allowing for a comprehensive and objective evaluation of potential sites considering various relevant factors such as technical aspects (available head, discharge, power, and accessibility of the site). MCA provides a structured framework to weight these factors and rank hydropower potential sites based on their overall relevancy and possibility of a sustainable future [7].

One of the most effective multi-criteria decision-making techniques is the Analytic Hierarchy Process (AHP) approach, applied when both objective and subjective factors need to be considered. It is helpful for the areas of expertise for building energy management, electric utility planning, resource allocation for energy, and planning for both conventional and renewable energy sources. Three steps comprise the AHP procedure: creating a hierarchy of goals, standards, and options; comparing criteria in pairs; and determining the relative weight of each component at every level (of the hierarchy) based on the results of the pairwise comparisons. According to [8], In order to attain uniformity in comparing criteria, the suggested a scale consisting of nine absolute values that indicate the degree of relative significance between two criteria. On this scale, a score of 1 denotes equal relevance, while a number of 9 denotes elements that are critically significant with respect to other criteria.

In the Silte Zone rural area, residents rely on unsustainable and harmful energy sources like cow dung and kerosene for cooking and heating [9]. These resources are expensive, time-consuming to acquire, and detrimental to health. Additionally, traditional farming practices constrain economic opportunities for women and children. In order to provide the community with a cost-effective and environmentally friendly energy source, the Furfuro River has the potential to provide a clean and affordable source of energy for people in the catchment.

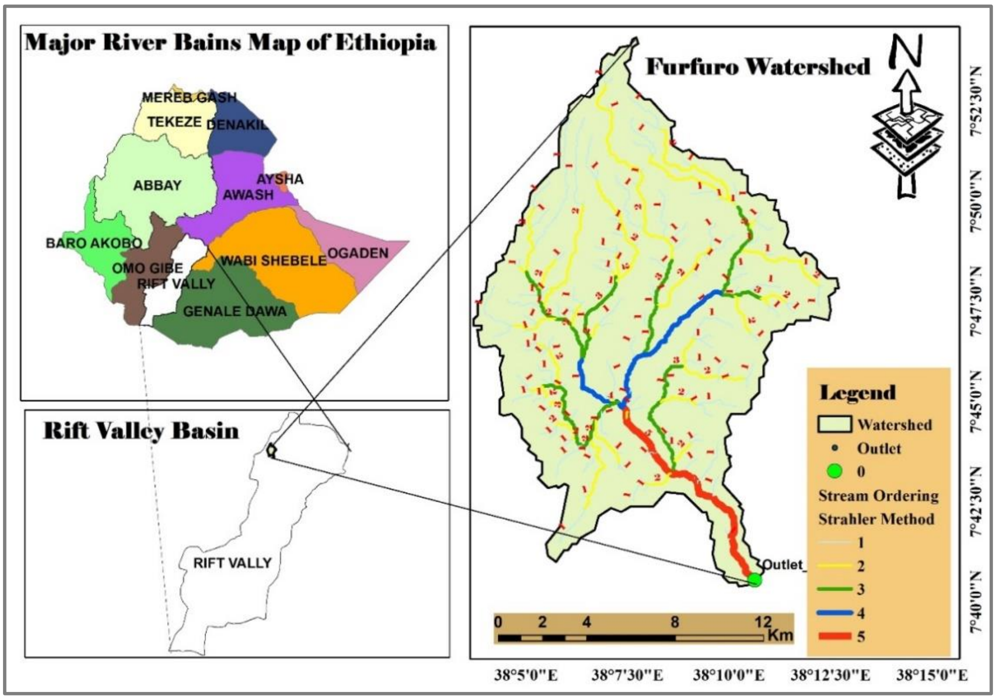

Figure 1. *Location map of Furfuro Watershed.*

1.1. Selecting a Suitable Hydropower Site Using AHP

An approach to multicriteria decision-making that uses mathematics is called the Analytic Hierarchy Process (AHP) that organizes decision considerations into a hierarchical problem structure [8]. AHP is a widely recognized method for prioritizing and choosing the optimum course of action in complicated decision-making challenges. AHP's primary objective is to help decision-makers solve difficult issues by organizing the multi-criteria decision-making criterion hierarchy.

To determine which theoretical hydropower prospective locations are the most promising, AHP was selected as a multi-criteria decision-making method. Five criteria were used to assess the potential of each site: power, discharge, head, accessibility, and distance to the nearest town. The AHP employed these criteria to rank the sites and identify the most suitable ones.

The application of AHP to decision-making involves four steps [10]: first, structuring the problem into a hierarchical model; second, conducting pairwise comparisons between criteria to obtain a comparison matrix; third, performing pairwise comparisons of alternatives to obtain another matrix; and finally, aggregating all the priorities.

1.2. Site Suitability Selection Criteria Objective and Alternatives

The objective of using the AHP process in this study is to select the best theoretical hydropower potential site from four sub-basins (31, 29, 24, and 25) as an alternative site. Based on a literature review of previous studies for small hydropower potential assessment and specific conditions of Furfuro watershed data availability, five criteria are considered the main factors for this study. These are the criteria by which this study chose the best hydroelectric location among the options:

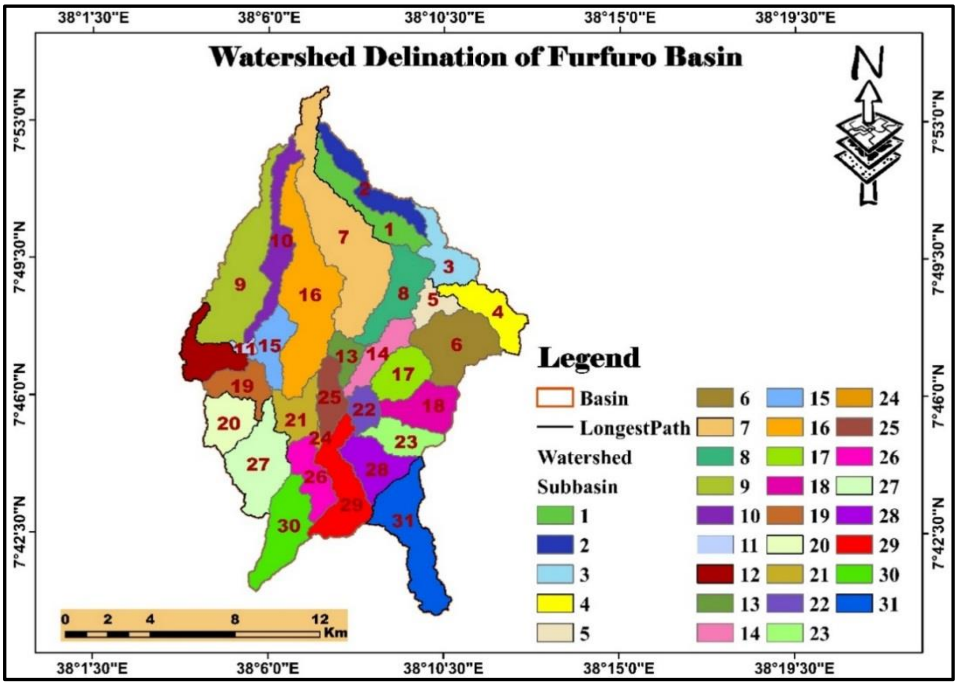

Figure 2. Selected Hydropower Potential site.

2. Materials and Methods

2.1. Study Area Description

Furfuro River is a perennial river located in the Wulbareg Woreda Silte zone. The coordinates of the river are Latitude 7°40′0″ to 7°54′45″N and Longitude 37°58′50″ to 38°18′38″E (Figure 1). Furfuro River has a few tributaries and seasonal streams at which they are all joined together to produce the high floods in the rainy season. Furfuro river catchment is located in Rift Valley sub basin covering an area of around 209.465 km^2. It rises on the high Silte plateau and descends downwards joining the Dijo River and altogether surface flow ended in Lake Shala. The highest point elevation in the northern part of the catchment is about 2668m, and the lowest point of the watershed where the dam outlet fixed is 1872 and altogether with Dijo River the surface flow ended in lake shala (elevation 1560m). In the study area, there is main valley with the direction of southeast, and the water resource of this valley is small springs at the higher lands of the main stream. In addition, there are many small valleys in the area draining towards the main valley.

2.1.1. Power

Hydropower potential is a function of the head and discharge combined. Locations for hydropower plant development are those with the optimum head and discharge balance. This criterion considers the impacts of head and outflow. Therefore, it has been considered the best criteria for prioritizing hydropower sites.

2.1.2. Discharge

One of the most crucial considerations when choosing a possible hydropower location is discharge. This study identified discharge as the second most influential factor affecting the potential electricity generation of a hydropower plant. Each selected hydropower site contains long term daily discharge data. The suitability of these sites was then measured based on these discharge values.

2.1.3. Head

The potential energy that makes the turbine rotate is due to the head of water above it. In Ethiopia, where conditions are often suitable for hydropower, the head plays a critical role in increasing the potential power generation. As a result, the availability of a higher head is one of the primary factors considered when determining whether a hydroelectric project location is acceptable.

2.1.4. Accessibility

As it affects the duration of research, the length of construction, and the cost of projects, accessibility is one of the most significant factors in determining project priority.

2.1.5. Distance

One of the primary elements influencing the project cost is the gap from the site to neighboring towns or settlements. To determine the most suitable hydropower site from those selected in the study area, suitability is estimated by assigning numerical values based on judgments for each site.

2.2. Selecting and Ranking Selected Sites

The primary purpose of selecting and ranking these sites based on comparison criteria is to identify the best location for a hydropower potential site. Economic feasibility is also crucial to project success. The study considers five main criteria that directly influence hydropower potential site selection. These criteria are then ranked according to their importance in determining a site's suitability. Saaty (1980) suggested these steps for selecting the most suitable site and ranking sites based on their suitability.

Step 1: Each criterion was given a number between 1 and 9 according to how relevant they were in order to generate the pairwise comparison matrix. The scale states that 1 denotes equal significance and 9 denotes great importance. An $n \times n$ matrix of ratings is produced by this method, where n is the number of elements taken into consideration.

Step 2: Then, each value in the column was divided by the total of the corresponding columns in the pairwise comparison matrix to get the normalized pairwise comparison matrix.

Step 3: The normalized values in each criterion's corresponding row of the pairwise comparison matrix is averaged to determine the weight of that criterion in AHP.

Step 4: For every site selection factor, the weights are calculated. The consistency index is calculated using this equation (CI).

$$CI = \frac{\lambda max - n}{n - 1} \tag{1}$$

Where: - CI, consistency index: n, amount of matrix elements that are being compared; and λmax, maximum Eigenvalue of the matrix for pairwise comparison.

AHP is used to break down a complex problem into a hierarchy containing all its essential elements. The final goal of the decision analysis is indicated at the highest level. From the main objective to the more intricate elements, the hierarchy then changes. It's used to obtain a priority score for each alternative site during hydropower potential site assessment. To calculate the overall priority score (SI) of the first alternative site in the study area, the following equation is used, which considers both individual site scores and the combined weights of the criteria [11].

$$SI = \sum_{j=1}^{n} Wj * Xij \tag{2}$$

Where: - Wj aggregated composite weight (Wj) combines the weights of objectives and criteria. Xij is the standardized criteria value for the i^{th} alternative site based on criteria j. Here, i represents the alternative site, and Xij is the alternative site score value. The site suitability index is determined using the following formula, and all hydropower sites are ranked according to the index values. [12].

$$SI = (Pw * Pr) + (Qw * Qr) + (Hw * Hr) + (Aw * Ar) + (Dw * Dr) \tag{3}$$

Where: - SI, the study area's most appropriate hydropower site is determined through a dimensionless site suitability index. 'w' represents the average weight assigned to each normalized criterion. 'r' represents the weighted score for each criterion based on a linear combination of ratings. Capital letters symbolize the criteria: P-Power, Q-Discharge, H-Head, A-Accessibility, and D- Distance.

Table 1. Saaty's Scale of Intensity, Relative Importance, Source [8].

Intensity of Importance	Definition
1	Equal importance
3	moderate importance one over another
5	Essential or strong importance
7	Very strong importance
9	Extreme importance
2,44,6,8	Intermediate values between the two adjacent judgments

3. Results and Discussion

3.1. Prioritization of Hydropower Potential Sites Using AHP

In order to help local decision-makers make a rational choice about which sites to prioritize for selected sites, the sites' ranking is essential. Many factors influence the ranking of sites; however, only power, discharge, head, accessibility, and distance of the site have been considered in this study due to data restrictions.

3.1.1. Pair-wise Comparison of Criteria

Pairwise comparison is the technique of evaluating the relative importance of many elements or criteria by comparing them in pairs. This method helps to determine if two criteria have equal weight or if one holds greater importance for a specific problem. simplifying a challenging issue and making it easier to decide on fair weights for several factors. The intensity of the significance scale from is used to give the relative relevance of one criterion to another for each member of the pairwise comparison matrix.

Table 2. Matrix of Pairwise Comparisons.

Criteria	Power	Discharge	Head	Accessibility	Distance
Power	1	2	2	4	5
Discharge	1/2	1	2	5	4
Head	1/2	1/2	1	4	5
Accessibility	1/4	1/5	1/4	1	3
Distance	1/5	1/4	1/5	1/3	1
Sum	2.45	3.95	5.45	14.3	18

3.1.2. Normalization of Matrix

To normalize the pairwise comparison matrix, divide each column element by the total of the columns that correspond to it. The process makes sure that each criterion has a weight between 0 and 1, with a larger weight denoting a criterion's stronger significance to determining the most suitable prospective hydropower locations.

Table 3. Normalization of the Matrix.

Criteria	Power	Discharge	Head	Accessibility	Distance
Power	0.41	0.51	0.37	0.28	0.28
Discharge	0.20	0.25	0.37	0.35	0.22
Head	0.20	0.13	0.18	0.28	0.28
Accessibility	0.10	0.05	0.05	0.07	0.17
Distance	0.08	0.06	0.04	0.02	0.06

3.1.3. Critical Weight Calculation

After normalizing the matrix, the critical weights were calculated as the average of the corresponding values in each column, as shown in the Table 4.

Table 4. Critical Weight Calculation.

Criteria	Power	Discharge	Head	Accessibility	Distance	Criteria Weight
Power	0.41	0.51	0.37	0.28	0.28	0.37

Criteria	Power	Discharge	Head	Accessibility	Distance	Criteria Weight
Discharge	0.20	0.25	0.37	0.35	0.22	0.28
Head	0.20	0.13	0.18	0.28	0.28	0.21
Accessibility	0.10	0.05	0.05	0.07	0.17	0.09
Distance	0.08	0.06	0.04	0.02	0.06	0.05

3.1.4. Calculating the Consistency Matrix

Pair-wise comparisons' usefulness depends on subjective assessment, which could provide arbitrary outcomes, Therefore, an assessment is required. A pair-wise comparison matrix's consistency is assessed using a numerical measure known as the consistency ratio (CR), as proposed in the Analytic Hierarchy Process (AHP) by [8]. This measure shows the proportion of the average consistency index (RI) to the consistency index (CI), as shown in equation (4).

$$CR = \frac{CI}{RI} \quad (4)$$

Where CI = consistency index and RI = random index values

Obtaining the largest Eigenvalue, λmax, which is obtained by multiplying the pairwise comparison matrix, is a prerequisite to calculating the consistency index value (Table 3) by the criteria weight values from the normalization matrix (Table 4). Afterwards, the weighted sum value is calculated by summing the values in the rows. The ratio of each weighted sum value to its corresponding criterion weight is then calculated, and the averaged ratio is equal to λmax. By performing this computation, the λmax value is 5.29. Then the consistency index value was obtained using Equation (1).

Table 5. *λ max Calculation.*

Weighted Sum Value	Criteria Weight	Ratio: WSV/CW	λ max
1.96	0.37	5.34	26.43/5=5.29
1.53	0.28	5.50	
1.15	0.21	5.35	
0.44	0.09	5.11	
0.27	0.05	5.13	
Sum		26.43	

$$CI = \frac{\lambda max - n}{n - 1} = \frac{5.29 - 5}{5 - 1} = 0.07$$

Where λmax is the principal biggest Eigen value and n is the number of rows and columns of matrix. Then, by taking the random index (RI) read from the table given by Saaty (1980) The appropriate value of RI for n = 5 is 1.12 based on the number of criteria., as shown Table 6 below.

Table 6. *Index of Random Consistency [8].*

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.6	0.9	1.12	1.24	1.3	1.41	1.45	1.49

$$CR = \frac{CI}{RI} = \frac{0.07}{1.12} = 0.06<0.01 \text{ (acceptable)}$$

According to Saaty, the CR value is more than 0.1; the best course of action is to go back and adjust the comparisons because it is not consistent enough. Consequently, 0.06 is a lower CR value than what is considered acceptable. Therefore, it is acceptable that the pairwise comparison's consistency.

Therefore, Power was given more weight than the other four prioritizing analysis criteria, which is 37%, followed by discharge (28%). The third factor is the head, which weighs 21%. The fourth is accessibility or road proximity, which is 9%. The last one is distance, which weighs 5%.

3.1.5. Standard Criteria

The combination of those five factors may be used to choose the best site among the alternatives. It is utilized to ascertain if the selected criteria could be maximized or decreased to acquire an overall appropriateness score for each selected hydropower prospective site.

Table 7. *For the best site selection, standardize to maximize and minimize.*

Criteria	Objective
Power	Maximize
Discharge	Maximize
Head	Maximize
Accessibility	Maximize

Criteria	Objective
Distance	Minimize

Table 8. Standardized Criterion Scores for selected Sites.

Site	P95 (KW)	Q95 (m^3/s)	Head (m)	Accessibility	Distance b/n Site and Town (Km)
1	1	1	1.00	0.50	2.31
2	0.48	0.91	0.42	1.00	1.00
3	0.02	0.52	0.07	0.50	1.21
4	0.06	0.29	0.15	0.50	3.95

Divide each value that falls under a criterion by the greatest value in the set to maximize that criterion. Conversely, minimizing a criterion involves dividing the lowest value in that criterion by each performance value. The standardized criteria table for selected sites is shown in Table 8.

3.2. Ranking the Furfuro Watershed's Hydropower Sites

For each pair of criteria, the ranking process is based on a pair-wise comparison matrix created using the Analytic Hierarchy Process (AHP). Through the application of weighted linear combination analysis, the weighted index is determined. This procedure includes standardizing each suitability score and assigning weight indexes to reflect their relative importance. The total site appropriateness score is then calculated by summing the weight indexes and standardized suitability. This score effectively evaluates the suitability of each hydropower site [13].

According to the selected five common criteria weights, the sum of the product of the linear combination for each criterion at each selected site and the average normalized matrix value from Table 3 are used. As a result, each hydropower site in the research area's suitability index is determined as shown in equation (5).

$$SI = (P * 0.37) + (Q * 0.28) + (H * 0.21) + (A * 0.09) + (D * 0.05) \quad (5)$$

Based on this analysis, the sites are then ranked based on their suitability index, prioritizing those most suitable for hydropower development. The site with the highest suitability index value is ranked first [14].

Table 9. The Final Suitability Ranks of Hydropower Sites in the Furfuro Watershed.

Site	P95 (KW)	Q95 (m^3/s)	Head (m)	Accessibility	Distance b/n Site and Town (Km)	Suitability Index (SI)	Rank
1	297.77	0.36	85	1.00	3.03	0.89	1
2	143.38	0.32	45	2.00	1.31	0.60	2
3	5.50	0.19	3	1	1.59	0.21	3
4	18.36	0.10	18	1.00	5.18	0.18	4

As shown in Table 9, the suitability ranking of the identified hydropower sites. Site 1 has the highest suitability index among all sites (0.89) and is ranked as the most suitable site, with a theoretical hydropower potential of 0.297 MW and 0.36 m^3/s discharge at 95% exceedance in the Furfuro River. In contrast, Site 4 is the least suitable site with a theoretical hydropower potential of 0.018 MW and 0.1 m^3/s discharge at 95% exceedance.

4. Conclusions

This study successfully prioritized potential hydropower sites along the Furfuro River in Ethiopia using the Analytic Hierarchy Process (AHP). By considering key factors such as power, discharge, head, accessibility, and distance, the AHP enabled a systematic evaluation and ranking of the sites.

The results highlight Site 1 as the most suitable option due to its favorable combination of factors. It possesses the highest theoretical hydropower potential and is relatively accessible. Conversely, Site 4, with lower potential and greater distance, was ranked as the least suitable. This research provides valuable insights for decision-makers in selecting optimal sites for hydropower development. By prioritizing sites based on their potential and feasibility, this approach can contribute to the sustainable development of hydropower resources in the region. However, further detailed technical and environmental assessments are necessary to fully evaluate the viability of these sites and minimize potential impacts.

Abbreviations

AHP	Analytic Hierarchy Process
CR	Consistency Ratio
MCA	Multi-criteria Analysis
SI	Suitability Index

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Author Contributions

Amsayaw Genet: Writing - original draft, writing review and editing, conceptualization investigation, methodology, data curation and analysis, procedural framework, model parameterization

Abebe Tadesse: Supervision, Validation, Overall Guidance, Writing, Reviewing, and Editing

Temesgen Zelalem: Conceptualization

Tensay Kifle: Data collection and review

Aynadis Ejargew: Methodology

Data Availability Statement

Data can be acquired upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Field

Amsayaw Genet: Hydropower, Hydrology, Reservoir Operation, Surface Water, Groundwater, Irrigation

Abebe Tadesse: Hydropower, Hydrology, surface water, groundwater, climate change, reservoir operation

Temesgen Zelalem: Hydropower, Hydrology, Reservoir operation, optimization, Surface Water, Groundwater

Tensay Kifle: Hydropower, Hydrology, Water Quality, Renewable Energy, Water Supply

Aynadis Ejargew: Hydropower, Water Supply, Hydrology, Water Quality, Irrigation