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Identifying Suitable Dam Locations in Al Dinder: Integrating GIS, Remote Sensing, and Hydrological Factors

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Abstract

This study evaluates the suitability of dam site locations in the Al Dinder region of Sudan using a GIS-based approach and weighted overlay analysis. Five key criteria were assessed: Stream Order, Slope, Soil Type, Precipitation, and Land Cover. Each criterion was analyzed to determine its impact on selecting optimal sites for dam construction. The results reveal that fourth-order streams offer the highest suitability due to their larger flow capacity, covering 11.4% of the area, while first-order streams, accounting for 48.9%, are less suitable. Slope analysis shows that 99.52% of the region features gentle slopes (0-5°), which are ideal for dam construction. Soil type analysis identifies Gleysols as the most favorable for dam foundations, covering 86.1% of the area. Precipitation levels, particularly in areas receiving 1200-2200 mm of rainfall, are deemed highly suitable for dam operations. The study further reveals that 96% of the land cover consists of barren land, which is advantageous for construction due to minimal land-use conflicts. A detailed cross-sectional profile analysis of six proposed dam sites identified Dam 5 as the most suitable location, offering stable terrain, a consistent cross-section, and favorable hydrological conditions. Other sites, such as Dam 1 and Dam 6, show promise but require additional engineering modifications. The study's findings contribute valuable insights into sustainable water resource management and infrastructure development in regions with similar environmental conditions. Key recommendations include further feasibility assessments, environmental impact analyses, and consideration of the social and economic benefits of dam construction.

1. Introduction

Hydrology is the scientific study of water in the Earth's atmosphere, on its surface, and in its subsurface environments. It plays a vital role in understanding the water cycle, managing water resources, and addressing various environmental challenges. Hydrology explores the distribution, movement, and quality of water, offering key insights for effective water management and sustainable development [1], [2], [3].

Hydrologic processes are highly complex, influenced by factors such as climate variability, land use changes, and human activities. These influences complicate water resource prediction and management, necessitating advanced analytical techniques and models to accurately simulate hydrologic phenomena [4], [5]. Additionally, hydrology integrates concepts from meteorology, geology, and environmental science, underscoring its interdisciplinary nature and the need for comprehensive approaches to tackle water-related issues [6], [7], [8].

Accurate assessment and forecasting of hydrologic variables are critical for mitigating the impacts of natural hazards like floods and droughts, ensuring water availability across various sectors, and maintaining ecological balance. Despite significant progress in hydrologic modeling and data analysis, challenges remain due to the inherent variability and uncertainty in hydrologic systems [9], [10], [11]. Continuous research and technological innovation are therefore essential to enhance our understanding and management of water resources in an evolving environment [12], [13].

Hydrologic analysis involves several key steps to understand and model water flow within a watershed, including determining flow direction, flow accumulation, stream identification, and stream ordering. Each step is fundamental to hydrologic modeling and effective water resource management [14], [15], [16].

1.1 Flow Direction

The first step in hydrologic analysis is determining flow direction, which identifies the path water follows as it moves across the landscape. This process relies on digital elevation models (DEMs) to find the steepest descent from each cell, guiding water flow. Accurate flow direction determination is crucial for subsequent hydrologic analysis, as it forms the basis for understanding water movement within a watershed [17], [18],[19].

1.2 Flow Accumulation

After determining flow direction, flow accumulation calculates the cumulative flow into each cell in a DEM. This helps identify areas where water is likely to accumulate, indicating potential sites for streams and rivers. Flow accumulation maps are crucial for understanding water distribution across the landscape and predicting areas prone to flooding or erosion [20], [21],[22].

1.3 Stream Identification

Stream identification involves delineating the network of watercourses within a watershed. Using flow accumulation data, thresholds are set to determine which cells have sufficient flow to be classified as streams. This step is vital for mapping the hydrologic network and understanding water movement pathways and connectivity,[23], [24], [25].

1.4 Stream Ordering

Stream ordering classifies streams based on their hierarchy within the hydrologic network. Techniques like the Strahler or Horton systems assign orders to streams, with higher orders representing larger watercourses formed by the convergence of smaller streams. Stream ordering is essential for understanding the structure and complexity of drainage networks, which is critical for watershed management and ecological studies [26], [27],[28].

1.5 Study Area

Al Dinder is located in the southeastern part of Sudan, as shown in Figure 1, bordered to the east by the Blue Nile River. It lies between the Gezira State to the north and the Blue Nile State to the south. The area is geographically situated between latitudes 12°30'N and 13°30'N and longitudes 34°00'E and 35°00'E. Al Dinder is strategically positioned along major agricultural zones, benefiting from its proximity to the Blue Nile, which provides essential water resources for irrigation and supports the region's agricultural activities.

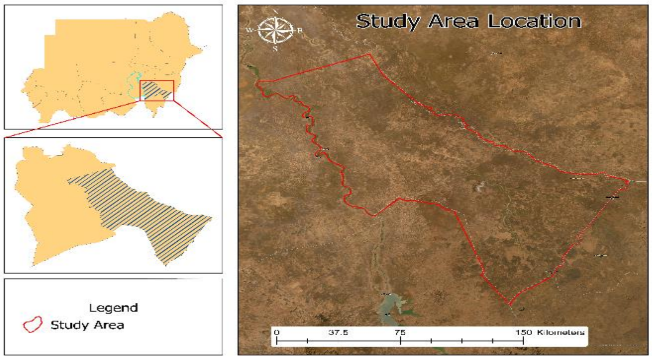

Figure 1. Study Area Location

1.6 Literature Review

Selecting suitable locations for dam construction necessitates thorough evaluation of environmental, hydrological, and geomorphological factors. Geographic Information Systems (GIS) and Remote Sensing (RS) are crucial tools in facilitating this decision-making process. Below is an overview of how various studies have employed GIS-based techniques to determine optimal dam sites:

a. Soba Valley, Sudan: GIS was applied to pinpoint optimal dam locations in the flood-prone Soba Valley. By evaluating factors such as slope, soil type, and hydrological data, flood risks were significantly mitigated [29].

b. Watersheds, Iran: GIS combined geomorphometric and topo-hydrological parameters to identify suitable check dam sites. This approach was key in reducing soil erosion and improving water resource management [30].

c. Mbeere North, Kenya: GIS was used to identify earth dam sites in arid regions, focusing on topography, land use, and hydrological conditions to alleviate water scarcity [31].

d. Alborz Province, Iran: GIS helped evaluate potential underground dam sites, offering sustainable water storage solutions in drought-prone areas [32].

e. Debre Berhan, Ethiopia: Geospatial tools were employed to select check dam locations, optimizing water storage and minimizing environmental impacts [33].

These studies highlight the effectiveness of GIS and remote sensing in enhancing water management and mitigating natural hazards through more informed dam site selection. Our study is particularly significant as it addresses the urgent need for dam construction in Al Dinder. Currently, the Dinder River is a seasonal river, flowing only during the rainy season, which limits the availability of this water resource. Constructing a dam would allow for water storage and year-round use, greatly benefiting agriculture. With a dam, farmers could cultivate crops year-round instead of depending solely on seasonal rainfall, thereby boosting agricultural productivity and sustainability.

2. Method

The flowchart of the method to be applied in the study is shown in Figure 2. This research adopts a systematic methodology to identify the optimal location for dam construction by utilizing a Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) and various geospatial data layers. The methodology is divided into specific phases: data collection and preprocessing, hydrological analysis, weighted overlay analysis, and final site selection.

2.1. Data Collection and Preprocessing

2.1.1 Digital Elevation Model (DEM):

The analysis begins with the SRTM (Shuttle Radar Topography Mission) Digital Elevation Model (DEM), which was extracted from radar data collected by the Space Shuttle Endeavour during an 11-day mission in February 2000. This DEM has a spatial resolution of 30 meters and serves as the core dataset for deriving essential hydrological features like stream networks and basin boundaries, both of which are critical for selecting suitable dam locations.

2.1.2 Slope:

Slope data is extracted from the DEM through terrain analysis. Slope is an important criterion for assessing land stability and suitability for dam infrastructure. Areas with gentle slopes are generally preferred for dam construction as they provide better support and reduce the risk of structural failure.

2.1.3 Stream Order:

Hydrological analysis will be applied to the DEM to delineate the stream networks. Using the Strahler method, streams will be classified into various orders, with higher-order streams being prioritized for dam sites due to their larger catchment areas and increased capacity to store and channel water.

2.1.4 Land Cover:

Land cover data will be sourced from the ESRI Sentinel dataset, with a spatial resolution of 10 meters. This information is critical for assessing the ecological and environmental impacts of the dam on different land cover types, such as forests, urban areas, and agricultural lands.

2.1.5 Soil Type:

Soil data will be obtained from the FAO database. The evaluation will focus on the suitability of soil types based on factors like stability, permeability, and erosion potential. These characteristics are fundamental to the dam's structural integrity and long-term sustainability.

2.1.6 Precipitation:

Precipitation data is sourced from the Global Precipitation Measurement (GPM) mission, an international collaboration led by NASA that began in 2014. This dataset integrates multi-sensor satellite observations with ground-based rain gauge measurements from stations to provide a comprehensive and accurate representation of rainfall patterns.

2.2 Hydrological Analysis

Stream Network Delineation: The SRTM DEM will be processed to fill any sinks, calculate flow direction, and create flow accumulation grids. These outputs will be used to delineate the stream network, which will then be classified into stream orders using the Strahler method. Higher-order streams are prioritized for dam site selection due to their capacity to support larger water storage systems.

Basins, representing catchment areas feeding into the stream network, will be delineated from the DEM. Basin analysis is crucial for understanding the hydrological dynamics of potential dam sites, especially concerning water volume and flow patterns.

2.3 Weighted Overlay Analysis

The dam site selection process involved a Weighted Overlay Analysis, where five key factors as shown in Table 1 were considered: slope, stream order, land cover, soil type, and precipitation. Each factor was weighted based on its importance using the Analytical Hierarchy Process (AHP).

2.3.1 Criteria Selection

The criteria used for this analysis were chosen based on their relevance to dam construction as shown in Figure 3:

Slope: Steeper slopes are more prone to landslides and erosion, making them less suitable for dam construction.

Stream Order: Higher stream orders indicate larger, more reliable water sources, which are essential for dam success.

Land Cover: Vegetation and land use affect water retention and soil stability.

Soil Type: The type of soil influences water storage capacity and the structural integrity of the dam.

Precipitation: Areas with higher rainfall are more likely to provide a consistent water supply for the dam.

2.3.2 Assigning Weights Using AHP

We used AHP to assign weights to each criterion as shown in Table 2 and Table 3. This involved pairwise comparisons between the criteria, using a scale of 1 to 5 as shown in Table 4, where:

1 = Equal importance
2 = Slightly more important
3 = Moderately more important
4 = Significantly more important
5 = Extremely more important

Table 1. Resolution of criteria for Dam Site Selection

Layer	Resolution
Slope	30 meters
Stream Order	30 meters
Land Cover	10 meters
Soil Type	Variable (FAO data)
Precipitation	Variable (NASA data)

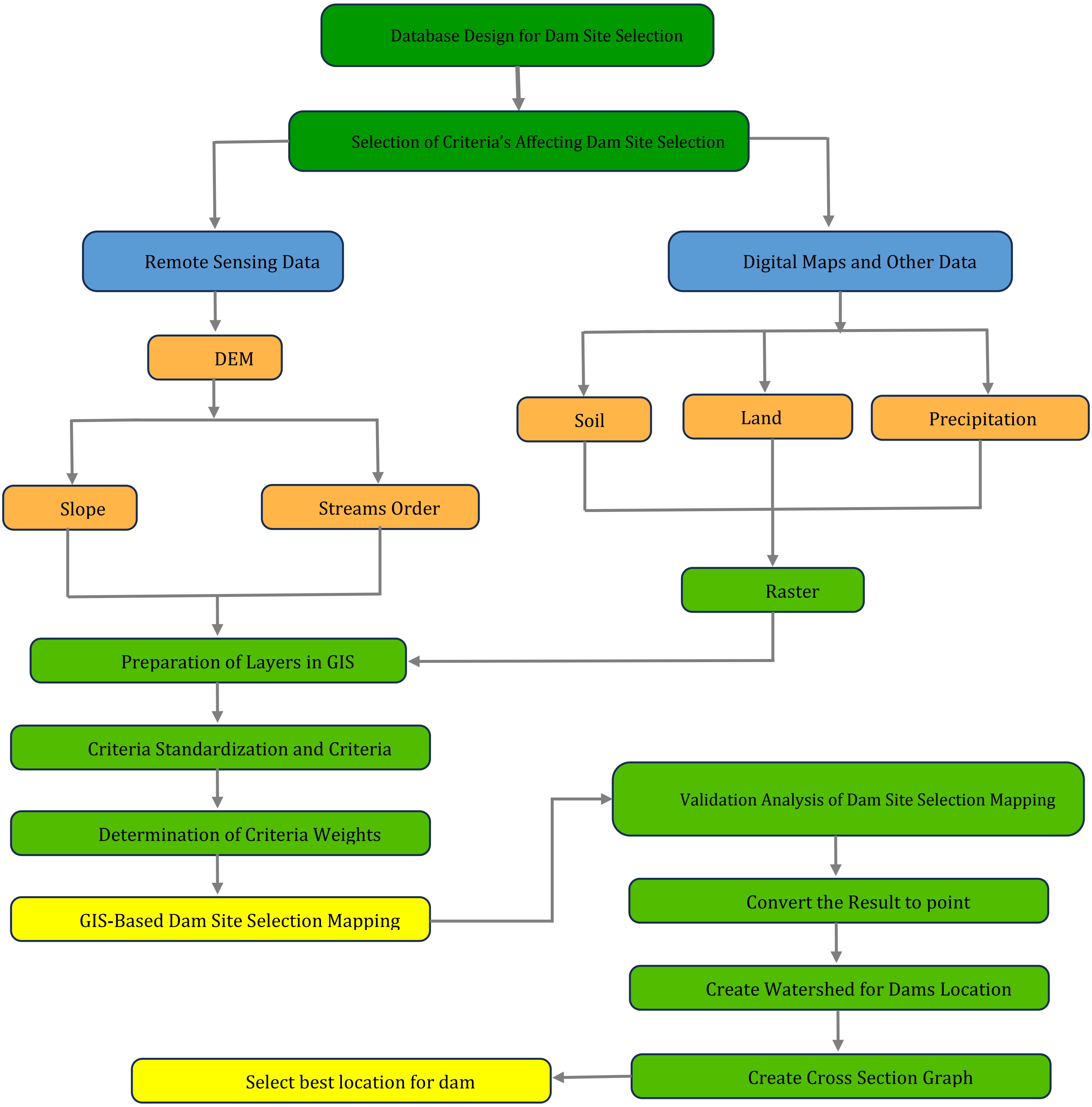

Figure 2. Flowchart of the method used in the study

Table2. A comparison matrix

Criteria	Stream Order	Slope	Soil Type	Precipitation	Land Cover
Stream Order	1	3	2	3	5
Slope	1/3	1	1	2	3
Soil Type	1/2	1	1	4	5
Precipitation	1/3	1/2	1/4	1	4
Land Cover	1/5	1/3	1/5	1/4	1

In this matrix:

- Slope is more important than Stream Order (moderate importance) and much more important than Soil Type.
- Stream Order is more important than Land Cover but less important than Slope.
- Precipitation is equally important as Stream Order.

2.3.3 Normalizing the Matrix

The next step was to normalize the matrix by dividing each value by the total of its respective column. This ensures that the values are on a comparable scale.

$$Sum\ of\ Each\ Column = \sum_{i=1}^{n} Matrix_{ij} \quad - 1$$

$$Normalized\ Value_{ij} = \frac{Matrix_{\ ij}}{Sum\ of\ each\ Column_{i}} \quad - 2$$

This process was repeated for each element in the matrix.

2.3.4 Calculating Final Weights

To determine the final weight for each criterion, we averaged the normalized values for each row as shown in Table 3. The formula used was:

$$Final\ Weight = \frac{\sum Normalized\ Values}{Number\ of\ Criteria} \quad - 3$$

2.4 Final Selection of Dam Location

The locations identified as most suitable through the weighted overlay analysis will be subjected to additional evaluation, incorporating further logistical, environmental, and socio-economic considerations.

3. Results

The results of this study provide a comprehensive evaluation of dam site suitability based on five key criteria: Stream Order, Slope, Soil Type, Precipitation, and Land Cover. Each factor was carefully analyzed to determine its impact on selecting optimal locations for dam construction, with results categorized into suitability levels ranging from "Very High" to "Very Low."

3.1 Stream Order

Stream order significantly influences the suitability of dam sites, as higher-order streams can handle larger water volumes. The results show that Fourth-order streams are the most favorable, covering 11.4% of the study area as shown in Figure 4, and classified as "Very High" suitability. Third-order streams, covering 14.6%, also offer a "High" suitability level. However, Second-order streams account for 25.1% of the area and are rated as "Medium" suitability. The largest proportion of the area, 48.9%, is covered by First-order streams, which are rated as "Low" in suitability, making them less desirable for dam construction due to their lower flow capacity.

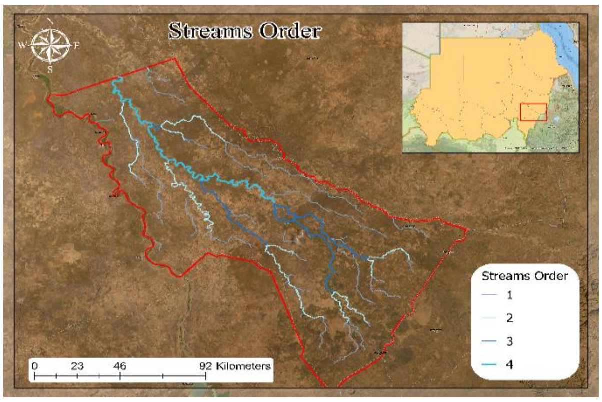

Figure 4. Streams Order

3.2 Slope

The slope of the land is a crucial factor in determining the stability and feasibility of dam construction.

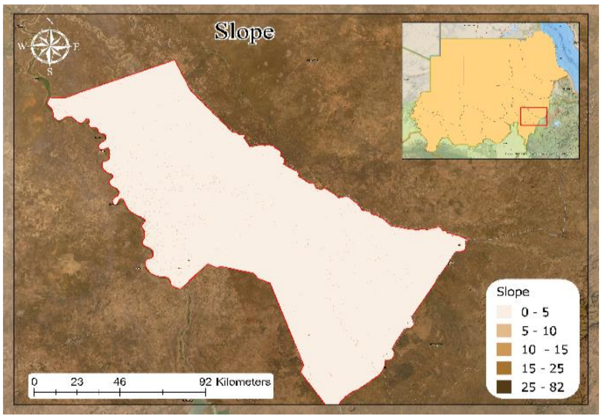

Figure 5. Slope

Table 3. AHP Calculation for Dam Site Selection Criteria

Criteria	Sum of each column	Relative Values	Final Weights
Stream Order	2.366	$\frac{1}{2.366} = 0.423$ $\frac{3}{5.833} = 0.541$ $\frac{2}{4.45} = 0.449$ $\frac{3}{10.25} = 0.293$ $\frac{5}{18} = 0.278$	0.391
Slope	5.833	$\frac{0.333}{2.366} = 0.141$ $\frac{1}{5.833} = 0.171$ $\frac{1}{4.45} = 0.225$ $\frac{2}{10.25} = 0.195$ $\frac{3}{18} = 0.167$	0.18
Soil Type	4.45	$\frac{0.5}{2.366} = 0.211$ $\frac{1}{5.833} = 0.171$ $\frac{1}{4.45} = 0.225$ $\frac{4}{10.25} = 0.39$ $\frac{5}{18} = 0.278$	0.255
Precipitation	10.25	$\frac{0.333}{2.366} = 0.141$ $\frac{0.5}{5.833} = 0.086$ $\frac{0.25}{4.45} = 0.056$ $\frac{1}{10.25} = 0.098$ $\frac{4}{18} = 0.222$	0.121
Land Cover	18	$\frac{0.2}{2.366} = 0.084$ $\frac{0.333}{5.833} = 0.057$ $\frac{0.2}{4.45} = 0.045$ $\frac{0.25}{10.25} = 0.024$ $\frac{1}{18} = 0.056$	0.053

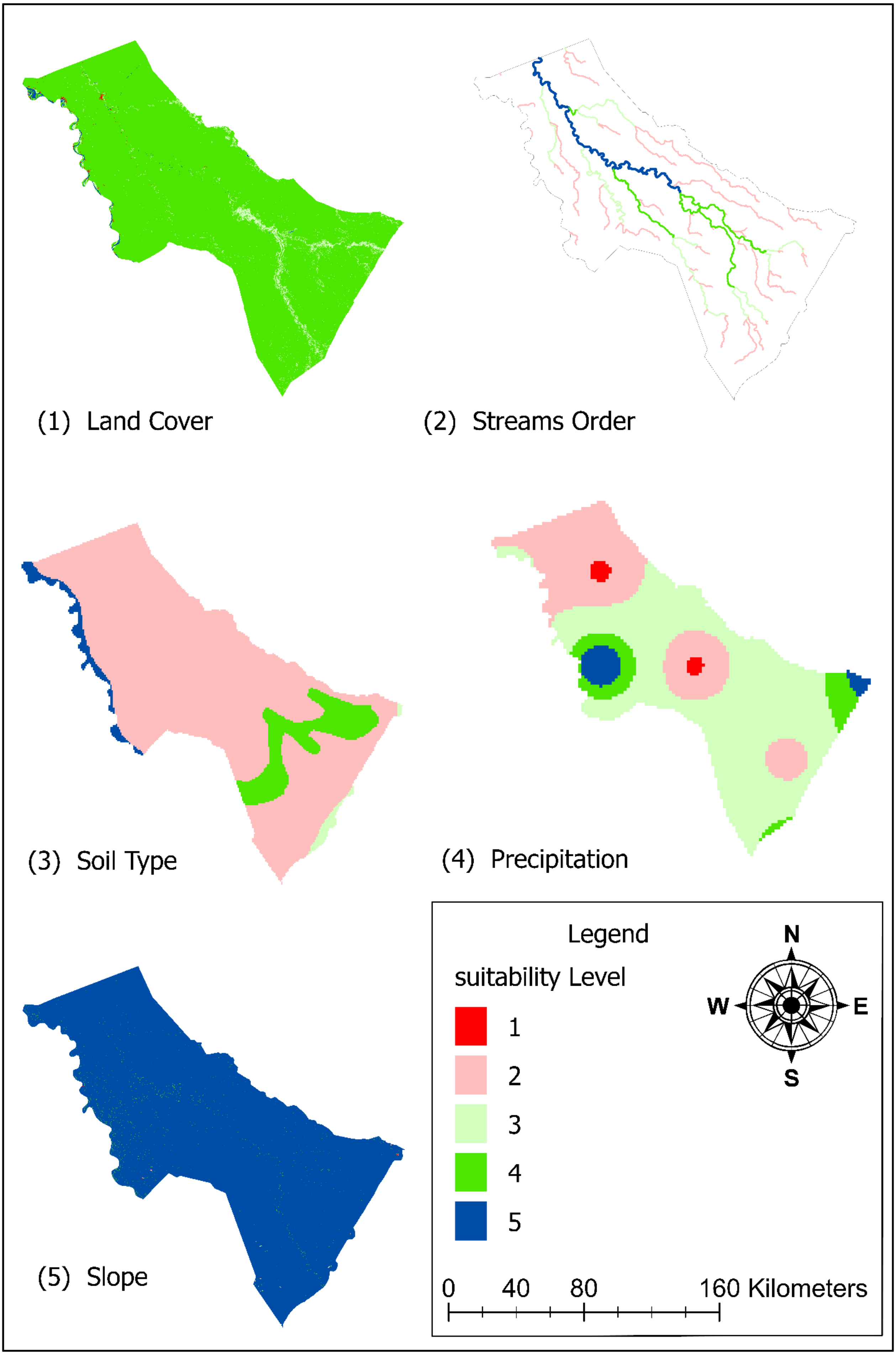
(1) Land Cover
(2) Streams Order
(3) Soil Type
(4) Precipitation
(5) Slope
Legend
suitability Level
1
2
3
4
5
N
W
E
S
0
40
80
160 Kilometers

Figure 3. Classified maps of standardized criteria for dam site selection

Table 4. Main criteria and suitability level used in dam site selection

Main criteria	Sub-criteria	Suitability value	Suitability level	Area-length	(%)
Streams Order	Fourth	5	Very High	204.2	11.4
	Third	4	Hight	263.0	14.6
	Second	3	Medium	450.2	25.1
	First	2	Low	878.6	48.9
Slope	0-5	5	Very High	16902.8	99.52
	5-10	4	Hight	73.6	0.434
	10-15	3	Medium	2.9	0.017
	15-20	2	Low	2.3	0.015
	20-82.4	1	Very Low	2.4	0.014
Soil Type	Cambisols (Jc)	5	Very High	492.5	2.9
	Vertisols (Vc)	4	Hight	1700.4	10
	Regosols (Be)	3	Medium	177.2	1
	Gleysols (Ge)	2	Low	14624.4	86.1
Precipitation	1200-2200	5	Very High	556.9	3.4
	430-1200	4	Hight	1137.8	6.9
	330-430	3	Medium	9702.1	59
	230-330	2	Low	4842.7	29.5
	20-230	1	Very Low	202.4	1.2
Land Cover	Water body	5	Very High	74.2	0.45
	Barren land	4	Hight	15839.9	96
	Agriculture	3	Medium	561.5	3.4
	Urban Land	2	Low	23.2	0.15

Nearly the entire study area (99.52%) consists of gentle slopes between 0-5°as shown in Figure 5, making these regions "Very High" in suitability for dam sites. This flat terrain is ideal for minimizing construction challenges. Steeper slopes, such as those between 5-10°, cover 0.434% of the area and are rated "High." As slopes increase beyond 10°, the suitability decreases sharply, with areas above 15° categorized as "Low" and "Very Low" suitability. These findings highlight the preference for flatter land when selecting dam sites to ensure long-term structural stability.

3.3 Soil Type

Soil type plays a vital role in supporting the foundation of dams. The dominant soil in the study area is Gleysols (Ge), covering 86.1 %, which is classified as "Very High" in suitability. This soil type provides the necessary strength and permeability characteristics ideal for dam construction. Vertisols (Vc) and Cambisols (Jc) soils, which make up 10 % and 2.9 % of the area respectively, are rated as "High" and "Medium" in suitability, indicating they can still support dam construction, but with some limitations. Regosols (Be) soil, covering just 1% of the area, has "Low" suitability, making it less ideal for dam construction due to potential issues like poor drainage.

3.4 Precipitation

Precipitation levels were analyzed to assess the availability of water for dams. The highest suitability for precipitation is found in areas that receive 1200-2200 mm of rainfall annually as shown in Figure 7, but these areas only make up 3.4% of the total area. The majority of the study area (59%) receives 330-430 mm of rainfall, which is classified as "Medium" suitability. This range is sufficient to ensure dam operations but may require additional water management strategies. Areas with lower rainfall, specifically 230-330 mm, cover 29.5% of the area and are rated "Low" suitability, while regions receiving 20-230 mm are rated "Very Low," accounting for 1.2% of the total area, making them unsuitable for dam sites due to inadequate water availability.

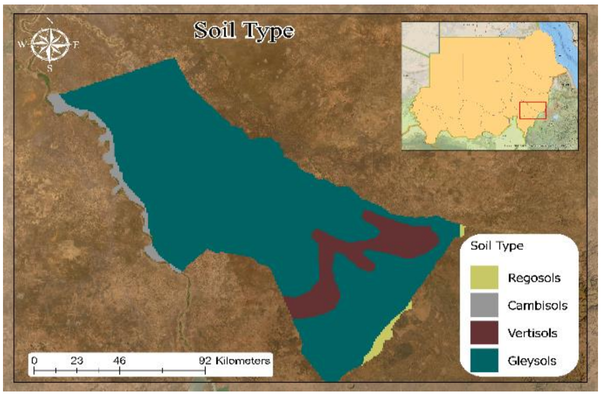

Figure 6. Soil type

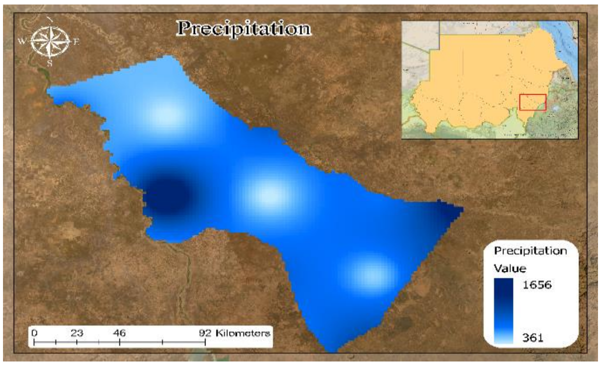

Figure 7. Precipitation

3.5 Land Cover

Land cover analysis reveals that the majority of the study area (96%) consists of barren land as shown in Figure 8, which is rated "High" in suitability for dam construction. This type of land is largely undeveloped, reducing potential conflicts with existing land use and making it highly favorable for infrastructure projects. Water bodies, though covering only 0.45% of the area, are rated as "Very High" suitability, highlighting their potential for use in reservoirs. Agricultural land, covering 3.4% of the area, is rated "Medium" suitability. Urban land, which covers only 0.15%, is rated as "Low" in suitability due to existing developments that would interfere with dam construction.

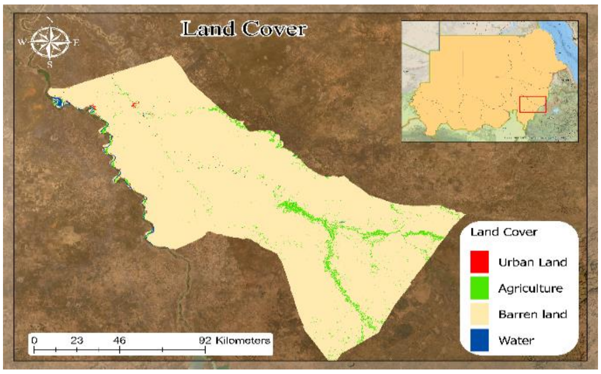

Figure 8. Land Cover

The results of the Weighted Overlay process show multiple optimal dam locations, as illustrated in Figure 9. We then analyzed the cross-sectional profiles of the six highest-suitability dams, as shown in Figure 10, to determine their suitability for construction. Factors such as terrain smoothness and topographical complexity were considered, as these influence water retention, dam stability, and the extent of engineering modifications required. Based on these criteria, the dams were ranked from most to least suitable.

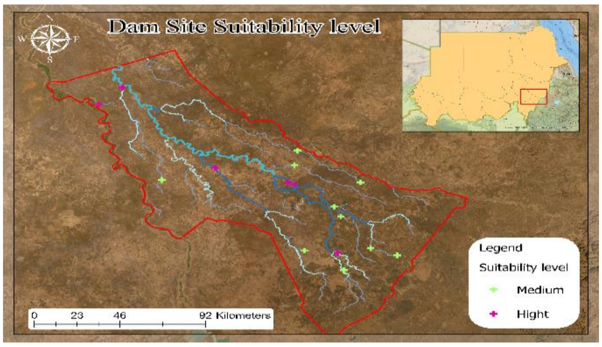

Figure 9. Dam site location suitability level

4. Discussion

Among the six proposed dam sites, Dam 5 emerged as the most suitable due to its stable terrain and consistent cross-section, which minimize the need for extensive modifications. Located at coordinates (34.86476001, 12.75545363) as shown in Figure 11, Dam 5 has a watershed area of 97.54 km^2. Its gentle slope and lack of significant elevation changes make it ideal for efficient water retention and minimal engineering interventions. Dam 1, situated at (34.03276001, 13.39545363) with a watershed area of 894.07 km^2, is also a strong candidate. It features a natural basin that is excellent for water storage. However, its lower elevation might present challenges in terms of water pressure and potential overflow management. Dam 6, located at (35.07276001, 12.30745363) with a watershed area of 1288.24 km^2, is another potential site. While it has a relatively stable profile, it may require some engineering adjustments to address variations in its cross-section. These modifications could involve additional costs and construction time. Dam 2, at coordinates (34.88076001, 12.97945363) with a watershed area of 397.42 km^2, has significant elevation changes that increase construction complexity. The terrain's variability could lead to higher costs and more extensive engineering work to ensure stability and effective water retention. Dam 3, located at (34.48076001, 12.86745363) with a watershed area of 290.34 km^2, faces similar issues with elevation changes. The uneven terrain would require substantial modifications to create a stable and efficient dam structure, making it less suitable compared to other sites. Dam 4, situated at (34.22476001, 12.78745363) with the largest watershed area of 1572.98 km^2, also has significant elevation changes.

These variations in terrain would necessitate extensive engineering interventions, increasing both the complexity and cost of construction. In summary, Dam 5 is the top choice due to its stable terrain and minimal need for modifications. Dam 1 and Dam 6 are viable options but come with certain challenges that need to be addressed. Dams 2, 3, and 4 are less suitable due to their complex topography and higher construction costs.

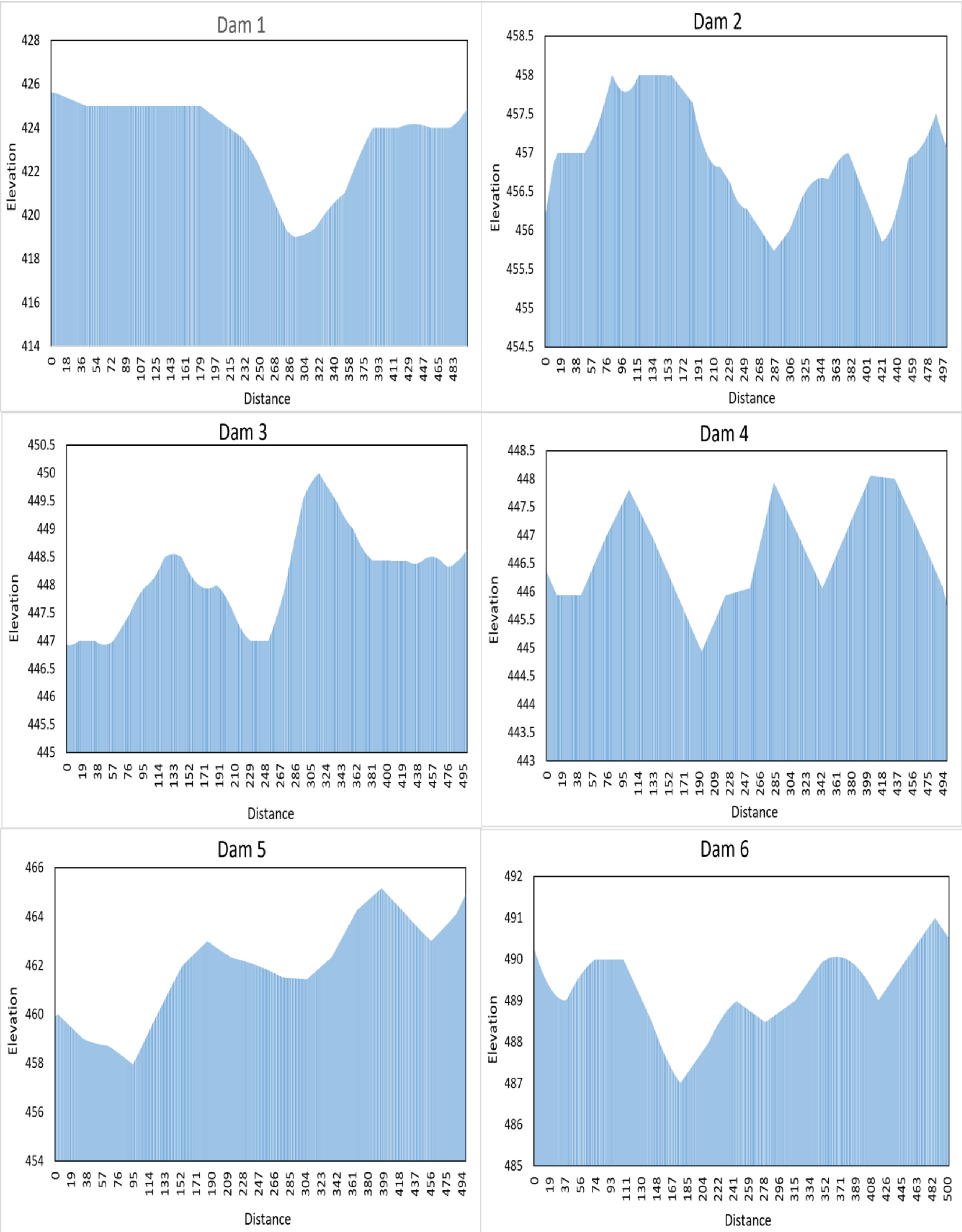

Figure 10. Cross Section of Proposed Location of DAM

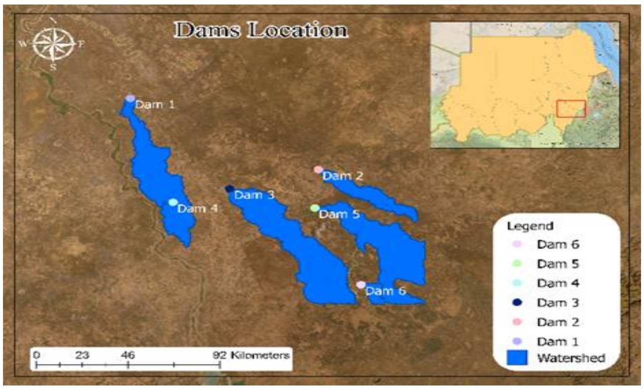

Figure 11. Dams' location and watershed

Among the six dams, Dam 4 is the largest as shown in table 5, covering an impressive 1572.976207 square kilometers. Following closely is Dam 6, with an area of 1288.235983 square kilometers. Dam 1 is moderately sized at 894.0714665 square kilometers. On the smaller side, we have Dam 2 and Dam 3, with areas of 397.4150784 and 290.3353194 square kilometers, respectively. The smallest of the group is Dam 5, spanning just 97.54228034 square kilometers. This variety in dam sizes showcases their different capacities and potential uses.

Table 5. Dam Sites with Coordinates, Watershed Areas, and Suitability Ratings

Dam	X	Y	Watershed Area	suitability
1	34.03276001	13.39545363	894.0714665	3
2	34.88076001	12.97945363	397.4150784	3
3	34.48076001	12.86745363	290.3353194	3
4	34.22476001	12.78745363	1572.976207	4
5	34.86476001	12.75545363	97.54228034	4
6	35.07276001	12.30745363	1288.235983	4

5. Conclusion

This study offers a thorough assessment of dam site suitability in the Al Dinder region of Sudan, utilizing GIS-based techniques and a weighted overlay analysis. We considered five key criteria: stream order, slope, soil type, precipitation, and land cover. Each factor was evaluated for its importance in dam construction, and suitability levels were assigned accordingly.

The results indicate that the most suitable dam sites possess several key features. Higher-order streams, particularly fourth-order streams, are ideal due to their larger flow capacity, followed by third-order streams. Gentle slopes, specifically those between 0-5°, are preferred for their stability and ease of construction. Suitable soil types, such as Gleysols and Vertisols, are highly favorable due to their stability and permeability. Adequate precipitation, with regions receiving 1200-2200 mm of annual rainfall, is crucial for ensuring sufficient water supply, while areas with less than 230 mm are deemed unsuitable. Additionally, barren or sparsely populated land cover is advantageous as it minimizes potential conflicts with existing land use and infrastructure. These characteristics collectively contribute to the overall suitability of a dam site, ensuring efficient water retention, stability, and minimal engineering modifications.

Based on these criteria, Dam 5 emerged as the most suitable location due to its stable terrain, consistent cross-section, and favorable hydrological conditions. It offers the potential for efficient water storage with minimal engineering modifications. While other sites, such as Dam 1 and Dam 6, also show promise, they may require additional considerations and potential modifications.

5.1 Key findings and recommendations:

- Dam 5 is the most suitable location based on the comprehensive analysis.
- Higher-order streams and gentle slopes are essential for dam site selection.
- Soil type and precipitation significantly impact suitability.
- Land cover can influence construction challenges and environmental impacts.
- Further analysis is needed for detailed design and feasibility assessments.
- Environmental impact assessments should be conducted to evaluate potential ecological and social implications.
- Economic and social benefits of dam construction should be carefully considered.
- Future research should focus on utilizing high-resolution DEMs, such as those from LiDAR or the TanDEM-X mission, with spatial resolutions of 1–12 meters to enhance the precision of hydrological and topographical analyses, enabling more accurate terrain modeling, stream network delineation, and flood risk assessments.

This study provides valuable insights for informed decision-making in selecting dam sites in the Al Dinder region. The methodologies and findings can be applied to other regions with similar hydrological and environmental conditions, contributing to sustainable water resource management and development.

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Author contributions

Hossam Aldeen Anwer contributed to the conceptualization, data collection, satellite imagery processing, analysis, manuscript editing, critical review and manuscript writing. **Abubakr Hassan** was responsible for supervision, critical review, manuscript editing and granted final approval for manuscript submission.

Conflicts of interest

The authors declare no conflicts of interest.

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