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Research article

Identification of Surface Water Storing Sites Using Topographic Wetness Index (TWI) and Normalized Difference Vegetation Index (NDVI)

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Abstract

Ethiopia is endowed with water and has a high runoff generation area compared to many countries, but the total stored water only goes up to approximately 36BCM. The problem of water shortage in Ethiopia emanates from the seasonality of rainfall and the lack of infrastructure for storage to capture excess runoff during flood seasons. Based on this premise, a method for a syndicate use of topography, land use and vegetation was applied to locate potential surface water storing sites. The steady-state Topographic Wetness Index (TWI) was used to represent the spatial distribution of water flow and water stagnating across the study area and the Normalized Difference Vegetation Index (NDVI) was used to detect surface water through multispectral analysis. With this approach, a number of water storing sites were identified in three categories: primary sources (water bodies based), secondary sources (Swampy/wetland based) and tertiary sources (the land based). A sample volume analysis for the 120354 water storing sites in category two, gives a 44.92BCM potential storing capacity with average depth of 4 m that improves the annual storage capacity of the country to 81BCM (8.6 % of annual renewable water sources). Finally, the research confirmed the TWI and NDVI based approach for water storing sites works without huge and complicated earth work; it is cost effective and has the potential of solving complex water resource challenges through spatial representation of water resource systems. Furthermore, the application of remote sensing captures temporal diversity and includes repetitive archives of data, enabling the monitoring of areas, even those that are inaccessible, at regular intervals.

1. Introduction

Water scarcity occurs where there are insufficient water resources available to meet average requirements. As such, balancing water-scarcity and population demand is the major challenge in many arid and semi-arid regions in the world **[1]**. Water storage is like an insurance mechanism that tackles consequences from this imbalance. Because of the intermittent nature of runoff events, storage is an integral part of the water harvesting system **[2]**. It serves as a buffer against variability of rainfall in distinct regimes and increases resilience against dry spells. Storage opens the possibilities for new economic activities where water is a production factor. Reliable access to irrigation water from storage opens a great potential for crop diversification. In addition, more reliable water supply is improved from storage **[2]**. **[3]** Describe in detail the adaptation of rainwater harvesting technology for where water resource to precipitation ratio is minimal. The approach was considered innovative and provided relief for agriculture and water supply.

Countries in sub-Saharan Africa store only about 4 % of their annual renewable flows, compared with 70 % - 90 % in many developed countries **[4]**. Reported in **[4]**, Cameroon has a renewable or stored water resource to precipitation ratio of 37 %, Uganda 21.05 %; Germany, conversely, has 62 % of stored water. Water storage is essential to ensure reliable sources of water for irrigation, water supply and hydropower and to provide a buffer for flood management.

The mean annual precipitation falling on Ethiopia amounts to 936 billion cubic meters **[5]**. However, due to very few stored water resources, the current capacity only goes up to almost 36 billion cubic meters by volume **[5]**. The country has only exploited a tenth of its precipitation heritage: there is a rechargeable source, a delivery system is needed; thus, water needs to be captured and stored. In such cases, rainwater harvested by local communities based on historical practices is the best option. As a process of concentrating rainfall as runoff from a catchment to be used in a target area, surface harvesting technologies have become important options to supply drinking water, develop irrigated agriculture and improve the ecosystem in dry areas. Seventeen provinces in China have adopted rain-water utilization technique, building 5.6 million tanks with a total capacity of 1.8 billion cubic meters, supplying drinking water for approximately 15 million people and supplemental irrigation for 1.2 million ha of land **[3]**.

The success of surface water harvesting systems depends heavily on the identification of suitable sites and their technical design **[6]**. For relatively small areas (in the range of several hundred hectares) a ground truth carried out by a number of experienced people will be the best technique to identify suitable areas for water harvesting. For medium range sizes of areas, the use of airplanes equipped with photographic equipment and for even larger areas, the application of remote sensing is considered to be the most relevant means of identification of areas suitable for certain techniques of water harvesting. For any of the above mentioned techniques, the application of suitable GIS techniques is vital **[7]**.

The selection of appropriate sites for different water harvesting technologies in larger areas is a great challenge **[7]**. GIS and remote sensing in hydrology and water resources have relieved some of the stress from the large time and effort that has been invested in realizing spatial and temporal patterns and characteristics of individual hydrologic processes by providing access to spatial and temporal information on watershed, regional, continental and global scales **[8]**. **[9]** further emphasizes the necessity of a GIS based system to identify areas with potential for surface water storing. This approach will provide a better guidance for targeting water storing research and developing projects in semi-arid regions. Surface water harvesting as a way of taking advantage of seasonal precipitation that would otherwise be lost as runoff can be a valuable technique to supplement the other sources by reducing dependence on rivers and groundwater sources. However, the selection of appropriate sites and determination of water harvesting on a large scale is difficult **[10]**. The applicability of water harvesting in Ethiopia is proper as seen in a quantitatively based classification done by Berhanu *et al.* **[11]** which showed that the high runoff generation area of the country has large coverage, indicating the availability of high surface water potential.

2. Materials and Methods

2.1 Study area description

Ethiopia is located in the northeastern corner of Africa between latitude 3° and 15° North and longitude 33° and 48° East (**Figure 1**). The country, which is the second most populous and the 9th largest in Africa, has an area of about 1.13 million km^2 of which 1.12 million km^2 is land area and the remaining 7,444 km^2 is water area (rivers, lakes, ponds) **[11]**. Although Ethiopia's complex relief defies easy classification, five topographic features are discernible. Owing to the complex relief, a complex meteorological framework is reflected by the distribution of annual precipitation as shown in **Figure 1**. In the Danakil depression, it is constantly less than 200 mm, but on the highlands it becomes more than 2200 mm. Mean annual potential evapotranspiration varies between 1700 and 2600 mm in arid and semi-arid areas and between 1600 and 2100 mm in dry sub-humid areas **[12]**-**[14]**.

2.2 Dataset

A reconditioned digital elevation model of Ethiopia at 30 m spatial resolution for topographic classification was obtained from USGS, which was accessed via (https://earthexplorer.usgs.gov). Landsat imagery to be used for land-use analysis for each month for specific years was downloaded. Depicted in **Table 1**, Landsat imagery for the entire study domain, for all months in 2015 in the form of landsat 8 OLI/TIRS C1 Level-1 with varying number of images covering the available spatial range. According to accuracy and availability, all bands corresponding to each month for selected years was evaluated. **Figure 2** shows the general steps followed in utilizing the acquired datasets to generate required output for the main objective (i.e. locating water storing sites).

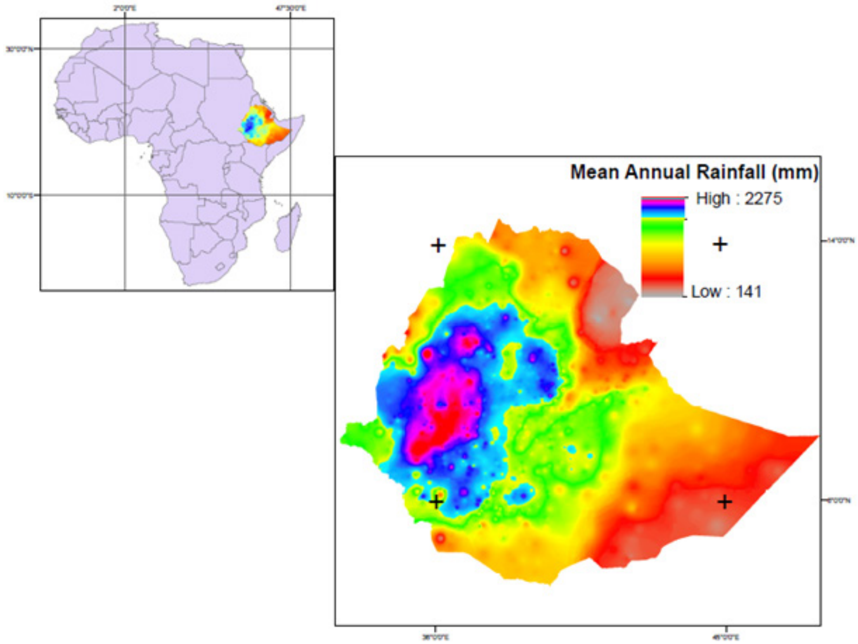

Figure 1: Location map of Ethiopia relative to Africa alongside Rainfall spatial distribution.

Table 1: List of acquired satellite image.

Type of acquired satellite imagery	Month of satellite overpass	Image collection acquired covering the study domain
Landsat 8 OLI/TIRS C1 L1	January	129
Landsat 8 OLI/TIRS C1 L1	February	108
Landsat 8 OLI/TIRS C1 L1	March	112
Landsat 8 OLI/TIRS C1 L1	April	122
Landsat 8 OLI/TIRS C1 L1	May	118
Landsat 8 OLI/TIRS C1 L1	June	105
Landsat 8 OLI/TIRS C1 L1	July	108
Landsat 8 OLI/TIRS C1 L1	August	114
Landsat 8 OLI/TIRS C1 L1	September	110
Landsat 8 OLI/TIRS C1 L1	October	118
Landsat 8 OLI/TIRS C1 L1	November	111
Landsat 8 OLI/TIRS C1 L1	December	124

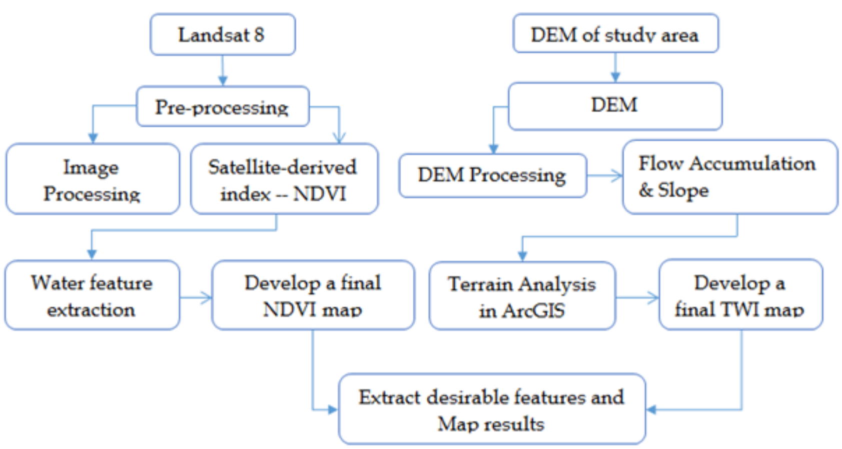

Figure 2: Conceptual framework for identifying potential water storing sites.

2.3 Criteria for mapping surface water storing sites

The analysis is based on the theory that the location of variable source areas of runoff generation and the distribution of water are influenced by soil characteristics, topography, vegetation and weather. As such, the Topographic Wetness Index (TWI) was used to address the topographical and soil-related aspect of the analysis, and the Normalized Difference Vegetation Index (NDVI) was used to analyze the soil and vegetation characteristics. Both, in combination, were expected to address locations for water harvesting throughout the study area. Input datasets were integrated and analyzed using ArcGIS.

2.4 Terrain Analysis – Topographic Wetness Index

Beven and Kirkby **[15]** developed an algorithm for predicting pattern soil water deficit from topography and soil hydraulic characteristics. Locating saturated areas is highly impractical due to data limitations and lack of understanding or proper surveying of the governing processes at scales from plots to catchments. These data involve devising a highly parameterized approach that models governing processes defining distribution of soil moisture in space and time **[16]**-**[19]**. An alternative approach for locating **[20]** saturated areas that take into account the major factors affecting the identification of potential water harvesting sites is the use of terrain indices. As such, in this paper, the steady-state topographic wetness index was used to represent the spatial distribution of water flow and water stagnating across the country. Topographic Wetness Index that is purely based on topography is a function of the upstream contributing area and slope **[17]**-**[19]**. It is based on a widely available DEM and was calculated using spatial analyst tools in ArcGIS. The popular formula for computing TWI, **[15].**

$$TWI = \ln\left(\frac{\alpha}{\tan\beta}\right) \quad (1)$$

Where is the upslope contributing area per unit contour length, this is a measure of the potential area that can deliver water via lateral flow pathways. And is the local slope gradient reflecting the local drainage potential. The TWI was manipulated in a GIS environment using surface analysis and hydrology tools to compute the flow accumulation and slope using DEM as input. These two attributes were computed separately in ArcGIS. Therefore, the GIS equivalent equation of TWI is as follows **[20]**-**[25]**.

$$TWI = \ln\left(\frac{(Flow\_accumulation)\times Pixlesize^2}{\tan(Slope(rad))}\right) \quad (2)$$

Flow accumulation was used as a method of identifying the upstream contributing area and estimating the overland flow. From the different approaches on calculating the contributing area, D8 (deterministic-eight node) was used implicitly defined in ArcGIS flow accumulation tool. This was used due to its simplicity and its adequacy to delineate specific catchment boundaries. A modification to TWI equation was made to account for undefined values for flow accumulation as well as for slope. Border pixel values have zero flow accumulation when used in ArcGIS, hence undefined output raster results are avoided by adding a unit magnitude during TWI computation. In a similar manner, slopes that reach a value of zero will also result, again, in an undefined pixel. A correction recommended for this was to add a tan function of an almost flat land to avoid division by zero. Having this in mind, the adjusted TWI computation adjusted as follows:

$$TWI = \ln\left(\frac{(Flow\_accumulation+1)\times Pixlesize^2}{"0.00565"+\tan(Slope(rad))}\right) \quad (3)$$

Where, 0.00565 is tan of a flat land close to zero slopes.

Accordingly, the results were expected to be in the form of a raster as a combination of the upstream contributing area and slope clearly signifying the soil water holding capacity. Once these results were obtained, re-categorization was required to group the values according to their representation.

Regarding ranges of TWI, a relative classification was selected for this study based on previous works. Most works involved depend on the resolution of the available DEM and in computing topographic attributes, classify TWI on unit ranges with values of over 10 being labeled as large values. The TWI results of over 10 have shown to have higher flows upon review with reference to known lakes and water bodies. These locations, as mentioned before, have lower slopes and are found usually downstream of the watershed. Owing to this, they have characteristics such as higher potential for higher soil moisture; hence they are areas of recharge with green land cover due to the presence of soil moisture. Considering the factors that influence runoff generation and distribution as well as stagnation, it is fair to say that the Topographic wetness index covers a major portion. Nevertheless, consideration of vegetation in terms of land use can make the hypothesis on which locating water resources is based on more solid. Some parameters not considered in TWI will also get a chance to be influential.

Primarily, wetlands are topographical lowlands and hence the DEM data offer a significant opportunity to delineate low lands from uplands as discussed previously for manipulation through terrain analysis using Topographic wetness index. Considering the second input: remote sensing satellites at different spatial, spectral, and temporal resolutions provide an enormous amount of data that have become primary sources, being extensively used for detecting and extracting surface water and its changes in recent decades **[26]**. Making use of these methods is to keep up with the current norms and exploit these desirable features as additional input for locating water harvesting points.

2.5 Land-use analysis-NDVI

More than 40 multispectral remote sensing-based indices have been developed and used to monitor water and vegetation properties. Among these, NDVI is the most widely used source of satellite data **[27]**, which is commonly calculated by using image data from polar orbiting satellites that carry sensors that detect radiation in red and infrared wavelengths **[27]**.

The NDVI was developed mainly for separating green vegetation from other surfaces. However, it also performed well for surface water detection **[26]**. GIS techniques were used to extract satellite data as well as for use in the mosaicking and analysis of the remotely sensed imagery. These near real time products generated were obtained for NDVI computation and are available at a 30-m spatial resolution and were obtained via Geo-TIFF format. Depending on the type of landsat imagery, the bands required for NDVI computation were filtered and used. From the 12 bands acquired corresponding to each image, two were selected as having the required band combination for NDVI computation.

Raster calculator in ArcGIS was used to transform the raw satellite data into NDVI values, to create a raster image that gives a measure of vegetation type, amount, and condition on land surfaces. After completing the pre-processing (i.e. filtering and mosaicking) of the satellite images, the NDVI values of the images were calculated in raster calculator using the following formula **[28]**-**[29]**.

$$NDVI = \left(\frac{NIR - R}{NIR + R}\right) \quad (4)$$

Where, R (0.4–0.7 mm) and NIR (0.75–1.1 mm) are reflectance in red and near infrared bands of the satellite imageries, respectively.

For visual interpretation of water bodies, the near-infrared (NIR) band is usually preferred, because NIR is strongly absorbed by water and is strongly reflected by the terrestrial vegetation and dry soil **[30]**. Thus, Band 5 was selected in this study due to its higher ability to discriminate water and dry/land areas. Band 4, corresponding to the visible Red bad (absorbed by leaf chlorophyll) was selected as the second band for the band combination representing NDVI. The computation of NDVI for landsat 8 imagery in ArcGIS' raster calculator is as follows:

$$NDVI = \left(\frac{Band5 - Band4}{Band5 + Band4}\right) \quad (5)$$

In order to avoid inaccuracies resulting from cloud cover, months January and February were selected for NDVI computation. A critical challenge, when dealing with remotely sensing data is cloud cover, especially in the tropics. To overcome this issue, a cloud free image should be selected, clouds need to be masked out or a median value of the image should be used. It goes without saying that the latter may compromise the accuracy of the result. The NDVI values were then classified according to the USGS 1998 classification **[31]**, **[32]** table. Alongside, the study in wetland mapping by **[33]** confirmed that values in the range -0.025 to 0.01 were regarded as the appropriate threshold values, which is in the range of swampy and wetlands in the USGS classification table. Upon this deduction, further classification would be ideal for locating potential water sources next to actual identified lakes (**Table 2**).

2.6 Water harvesting categories

Overlay in raster calculator in ArcGIS was used to select sites corresponding to both features. TWI values of over 15 (for the sake of selecting a narrowed yet most desirable range) and NDVI values of "light green vegetation", "swampy areas" and "water bodies" were targeted to develop nine possible combinations.

Table 2: The NDVI classification under Albedo values for different cover types.

Cover Type	NDVI range
Dense green leafy vegetation	0.500 – 1.000
Medium green leafy vegetation	0.140 – 0.500
Light green leafy vegetation	0.090 – 0.140
Bare soil	0.025 – 0.090
Swampy areas/wet lands	-0.046 – 0.025
Water Bodies	-1.000 - -0.046

3. Results and Discussion

3.1 Terrain analysis

The results for D8 flow accumulation with higher values indicate a greater area with large incoming accumulated water thereby influencing soil moisture. On the contrary, higher values from the slope computation indicate areas that are steep, which allows water to flow readily. The combination of these inputs (contributing area and slope) which yielded the TWI has results that range from 3.39 to 31.08.

The higher values indicate large contributing area coupled with low slope and hence a greater potential for water concentration and the lower values indicate high slopes where water is free to drain. The values obtained were reclassified and TWI ranges of 0-15, which signifyied suitability of water accumulation to be low, were disregarded. On the contrary, ranges with TWIs greater than 15, exhibit high flow concentration capacities which make them the ideal choices for potential water harvesting. The map in **Figure 3** shows this filtered category of TWI.

3.2 Land use analysis

NDVI value for January 2015 was initially mapped into eight categories based on the classification shown in **Table 2**. Upon manual division of land-water threshold, the study was able to find that the NDVI had in fact the ability to discriminate water and dry land areas well. The resultant land use map, shown in **Figure 4**, consists of three dominant land cover classes that were selected for appropriate water harvesting sites, namely light green vegetation, swampy areas/ wetlands and water bodies.

The percentage of the area coverage of these selected land cover types computed to see the potential extent for water storing sites (**Table 3**). The computed areas of known lakes were accurate when cross-checked to that of available hydro-sheds data. Although the percentage of a real coverage for swampy/wetlands is relatively small, the percentage by volume is quite large.

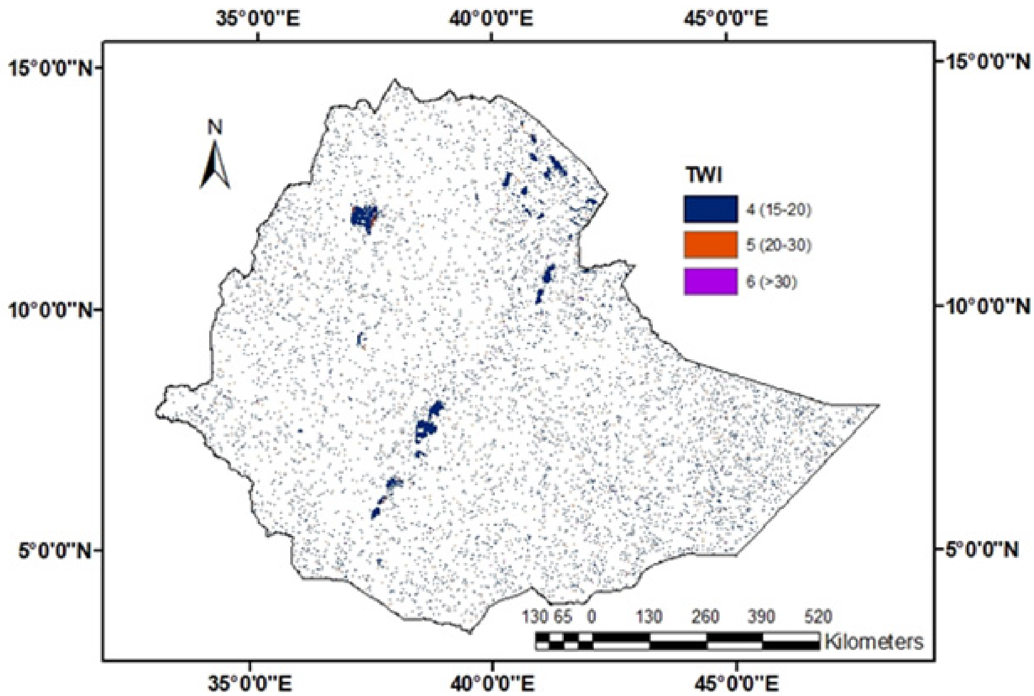

Figure 3: Desirable TWI classification map of Ethiopia surpassing a threshold value of 15.

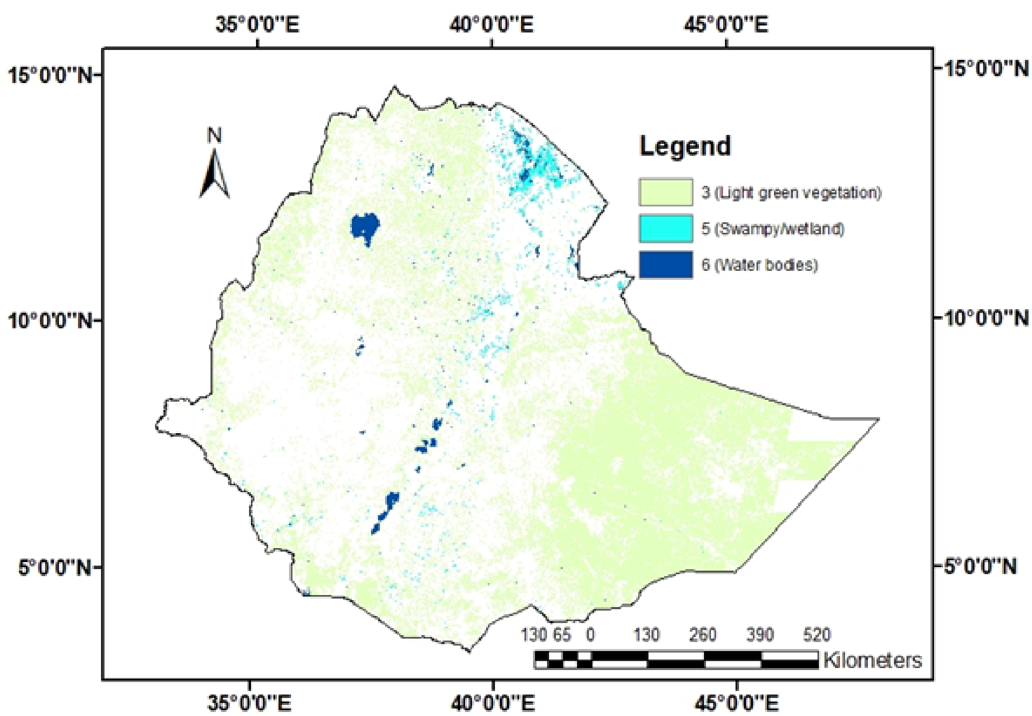

Figure 4: Spatial distribution of desirable NDVI map for RWH in Ethiopia.

Table 3: Desirable NDVI category of Ethiopia with areal coverage.

Category	Value	Areal coverage (%)
3	Light green vegetation	36.28
5	Swampy/wetland	1.35
6	Water bodies	0.85

3.3 Water harvesting categories

Locating optimal sites for water harvesting was based on both maps (i.e. the physically derived TWI maps as well as land use that influenced water holding capacity of the zones). This connection was made a reality as both features met the requirement for storing surface water and consist of three suitability values. Locations ideal for surface water storing under TWI properly signify sites that have the capacity for a greater water concentration. This was supplemented with NDVI values that again accurately indicated water bodies over land area. The joint use of these indices addressed soil characteristics, topography and vegetation condition. This joining is an advantage in the accuracy of the final results. As an illustration, certain scenarios were considered before joining these indices. A desirable NDVI alone would not be enough to identify water harvesting sites as it does not guarantee prolonged water concentration on that area which was made available with the presence of the TWI.

In a similar token, the TWI alone was not solely considered, as targets required being environmentally sustainable with land use study. The presence of a large TWI guarantees higher soil moisture which are greener due to the presence of soil moisture. The use of NDVI avoids selecting large forest bodies to avoid environmental impact associated with constructing water harvesting structures by deforestation. For this reason, the potential locations identified guarantee potential water existence, stagnation and are available with minimum amount of earth work and with minimal environmental impact.

Overlay options in raster calculator were used to make sure both TWI and NDVI were addressed to identify water harvesting locations. From the initial analysis using raster calculator, nine possible combinations were obtained, mapped in **Figure 5**. A script was written in ArcGIS' raster calculator where each grouping yielded the multi-class combination of water harvesting zones. The script, guided by the if-condition classified the three distinct, yet separate classes into the nine classes as shown in the legend of **Figure 5**.

According to the classification shown in **Figure 5**, a greater suitability for water harvesting is obtained from the combination of a TWI value higher than 30, indicating high flow concentration and an NDVI value in the range "water bodies". On the contrary, TWI values between 15-20 and an NDVI value in the range "light green vegetation" result in a relatively lower suitability for water harvesting.

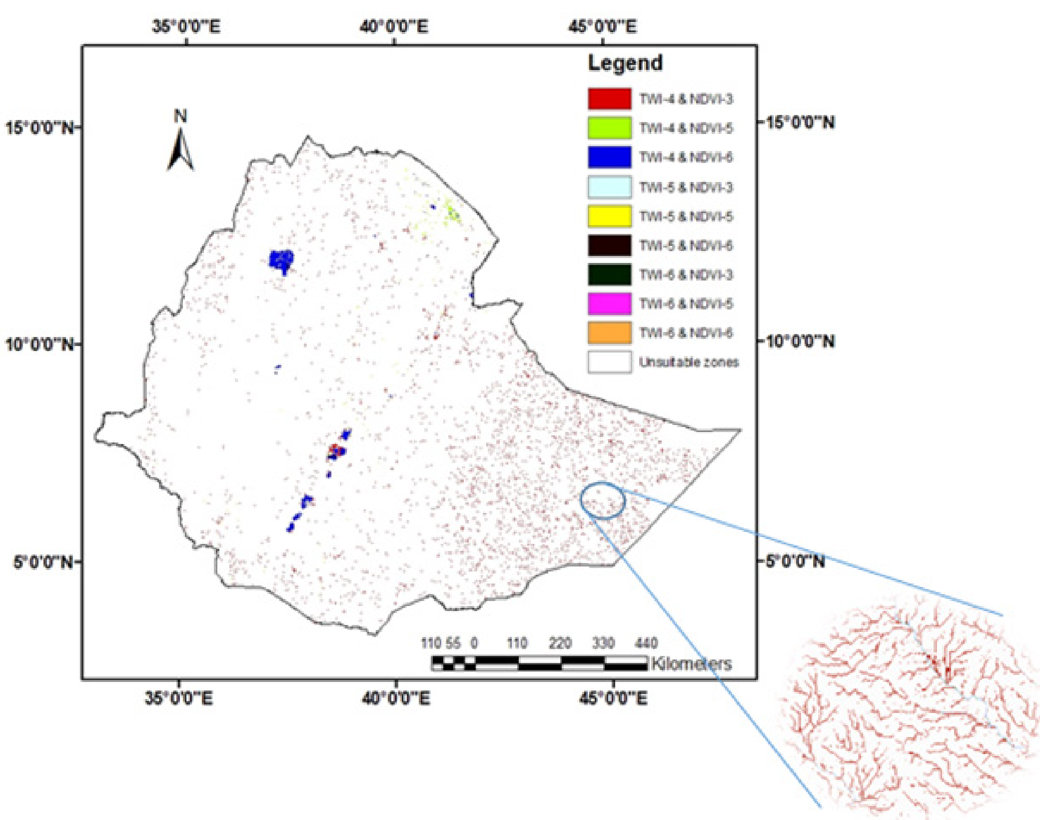

Figure 5: Spatial distribution of desirable NDVI map for RWH in Ethiopia.

As shown in **Figure 5**, the result is highly governed by the TWI value obtained which suffers from high streaking effects and did not indicate the spatial extent of the identified locations well enough. For this reason, a better approach that uses the "Identify features by location" in ArcGIS was used to give these locations some buffer zone. The tool identifies the three distinct NDVI classes that overlap with TWI ranges over 15. Before interpreting the obtained spatial result, further analysis was conducted that filtered these areas.

The surface water harvesting potential areas were identified with this criteria and methodology, and classified in three categories according to their desirability levels shown in **Figure 6**. The mapped results capture the spatial area of each zone in a much better way, providing a wider water harvesting area. These classifications indicate a greater percentage coverage area wise in the Primary sources, a lesser percentage coverage in the secondary sources and an even lesser landmass coverage in the tertiary sources.

The **first category** (Primary water sources) identifies the most desirable class which is water bodies themselves, where the maximum surface water harvesting zones cover 0.79 % of the country's landmass and is distributed in the locations shown in **Figure 6**. Up to 30,000 water-harvesting sites were located under this category, with areas ranging from 576 m^2 (for the smallest pixel zone) to 3,059 km^2. Since these locations are already known lakes, the accurate identification of these areas guarantees the reliability of the method. For evaluation purposes, the locations were cross-checked with an available water volume analysis report (site here).

The **second category** (Secondary sources) is the main finding of this research. This category identifies locations which are swampy areas/ wet lands found between categories "water bodies" and "bare-land" (in terms of spectra identification) that are intersected by the desirable values of the TWI. These locations are expected to be moderate surface water harvesting potential zones covering 0.47 % of the total landmass of Ethiopia. The identified areas range from 576m^2 to over 70 km^2 and amount to over 120,354 locations on a national scale. This category was given more attention in this study as it consists of locations that have not been located or exploited further. It is thus, the final output taken from the overall joint analysis. The potential volume of water harvesting with these identified sites was computed using an average water depth of 4 m (**Table 4**). Depending on the specific use and duration of supply the depth and the type of the water storing structure varies.

The **third category** (tertiary sources), was identified as land based water harvesting locations which is composed of light green vegetation that was selected considering the moisture collected on that location and as an outcome had resulted with a relatively good NDVI value. These locations were identified as preliminary level as water harvesting, where its feasibility will ascertain based on actual land based survey.

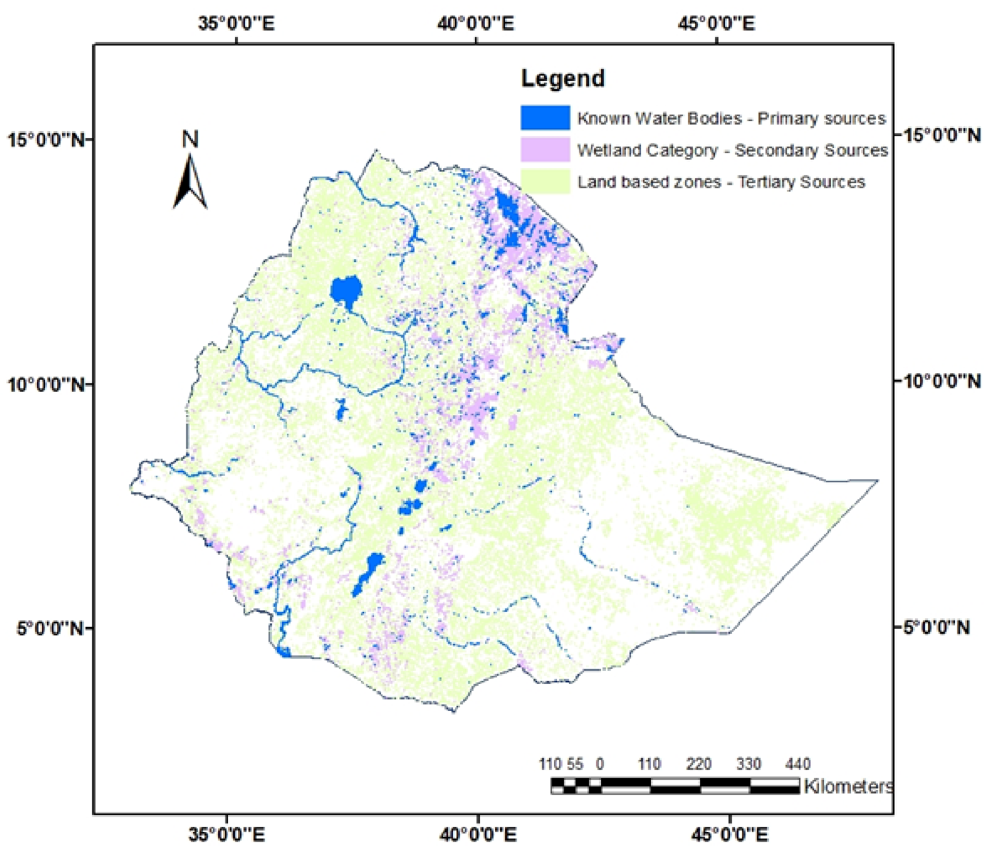

Figure 6: Water harvesting sites map of Ethiopia.

Table 4: Number and volume of identified storage sites in Ethiopia under Second Sources .

Areal range	Number of identified Storage sites	Area (km^2)	Average Volume (BCM)
Below 1ha	93189	168.20	0.61
From 1 ha to 5 ha	14168	330.73	1.32
From 5 ha to 10 ha	4137	293.75	1.17
From 10 ha to 18 ha	2704	364.10	1.46
Over 18 ha	6156	10091.00	40.36
Total	120354	11247.78	44.92

4. Conclusion

The utilization of a GIS-based approach combined with satellite imagery to determine water storing sites has shown an increased accuracy of locating areas with concentrated runoff. This was achieved through the integration of physical characteristics, manipulated through the use of Topographic Wetness Index (TWI) and land use/ land cover characteristics obtained through the use of the Normalized Difference Vegetation Index (NDVI). Water storing sites using a combination of soil characteristics, topography, vegetation and weather were identified and presented consisting of three suitability values. This sites identified in this research categorized into three, based on their land use conditions as primary sources (water-bodies based), secondary sources (Swampy/wetland based) and tertiary sources (land-based). Since the water-body based sites have known area and volume, and the land-based sites needs further field survey, their potential volume was not estimated in this research. On the contrary, the 120354 potential sites, in the second category, have 44.92BCM storing capacity with an average depth of 4m that improves the annual storage capacity of the country to 81BCM (8.6 % of annual renewable water sources). Finally, this research concludes that the use of GIS, TWI and NDVI based water storing sites identification in different categories comprises work without huge and complicated earth work, cost effective and has a potential to solve complex water resource challenges through spatial representation of water resource systems. Therefore, the approach is recommended for planning different water harvesting developments.

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