Flood Risk Mapping: Quantifying Topographic Wetness Index to determine Flood Risk Zones for Mutoko District in Zimbabwe.

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Abstract

Slope and topography help to describe the shape and relief of the land, allowing the hydrological and terrain analysis of a region by generating topographic wetness index (TWI). In this study the TWI is calculated using a digital elevation model raster layer. Spatial analyst tool and map algebra in ArcGIS was utilized to calculate slope, flow direction, flow accumulation, radian of slope, flow accumulation scaled, tan of slope, and ultimately TWI. Given that the TWI concept is less suitable in flat areas due to undefined flow directions, Mutoko District was chosen for this study due to its variations in topography. The index help to quantify topographic control on hydrologic processes, terrain driven variation in soil moisture, and is highly correlated with several soil attributes such as horizon depth, silt percentage, organic matter content and phosphorous. However, TWI utilizes topographic elements of landscape to determine water flow and accumulation, and does not take into account additional information such as soil type or rainfall, which would be necessary for comprehensive assessment of flood risk zones. Availability of meteorological and hydrological data in addition to a digital elevation model (DEM), provides a more dynamic approach for comprehensive analysis, allowing dynamic simulations of spatially distributed water storage that can be used to derive alternative wetness indices.

Key Words

Digital Elevation Model, Hydrological Analysis, Topographic wetness index, Flood risk

1. Introduction

The significance of topography in the distribution of water and energy within natural landscapes has been noted by various scholars. Extraction of topographic data from digital elevation models (DEMs) has been made possible by the use of satellites and drone imagery has been utilized as an alternative to traditional surveys (Lewis and Holden, 2012). Increasing quality and resolution of DEM products, through raster processing methodologies, has expanded the capabilities of GIS and its integration with water resources models, have seen the use of DEMs as a source of topographic and surface drainage information (Buchanan et al., 2014).

DEMs are widely used in hydrologic and geologic analyses, hazard monitoring, natural resources exploration, and agricultural management, amongst others (Grabsa et al., 2009; Nucifera & Sutanto, 2018). A digital elevation model (DEM) is a 3D representation of a terrain's surface, created from terrain elevation data. According to the United States Geological Survey (USGS) Fact Sheet (2000), DEM data are arrays of regularly spaced elevation values referenced horizontally, either to the Universal Transverse Mercator (UTM) projection or geographic coordinate system (GCS).

Hydrologic applications of the DEM include groundwater modeling, estimation of the volume of proposed reservoirs, determining landslide probability and flood prone area mapping. DEMs are commonly generated with data collected using remote sensing and land surveying techniques. Remote sensing data from satellites provide elevation data for various areas of interest. In this study, DEMs are utilized to support of hydrologic and water resources investigations with respect to the derivation of topographic data in order to generate a Topographic Wetness Index (TWI). The subject matter covered in this research is centered on DEM of natural landscapes for Mutoko District in Zimbabwe.

2. Literature Background

Topographic indices depends on the quality and resolution of the DEM from which they were derived (Sorensen and Seibert, 2007). Though input of data affect the performance of wetness indices, increased DEM resolution is not an indication of better performance as ground water flow is less likely to follow small-scale topography.

Topographic wetness index is used to quantify topographic controls on hydrological processes, and TWI can also be used to characterize biological processes including forest site quality, vegetation patterns, and annual net primary production (Beven and Kirkby, 1979; Sorenson et al., 2006).

2.1 Flow Routing Algorithms

Flow routing algorithms helps to identify stream channels at various spatial resolutions generated on the condition that water follows the steepest route along a relief and accumulates in low lying areas and depressions (Zhang et al., 2007b; Yang et al., 2010). TWI can be calculated with different flow-routing, slope and flow width algorithms. A flow accumulation algorithm can determine the ability of the TWI to predict soil moisture, while the flow width and slope algorithms may have minor effects (Kopecký et al., 2021). The single flow (D8) algorithm is widely used for flow routing. The topographic wet index was developed by Beven and Kirkby within the runoff model. The TWI is unit less and is given by: ***Ln (a/tan b)***,

Where ***a*** is the local upslope area draining through a certain point per unit contour length, and ***tan b*** is the local slope in radians. The TWI has been used to study spatial scale effects on hydrological processes.

3. Study Area, Material and Methods

The research was conducted using DEM for Mutoko District obtained from United States Geological Survey (USGS) Shuttle Radar Topography Mission (SRTM) at 1 Arc Second Global (30m) resolution (.

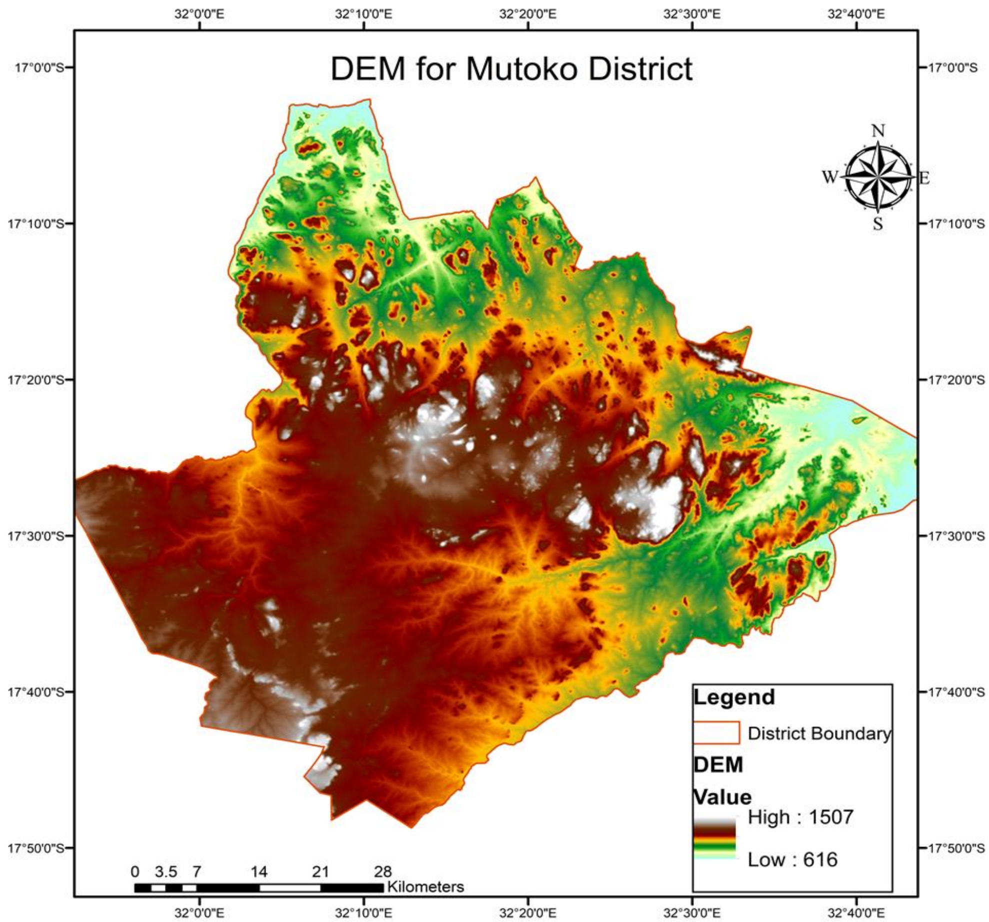

Figure 1: DEM for Mutoko District

Mutoko District is located in Mashonaland Central Province of Zimbabwe, 142 kilometers from Harare capital. The rain season for Mutoko starts in October and ending in April, and the months of November, December, January and February have average rainfall days ranging between 10 and 20 days, whilst high average temperatures are experienced from the month of August to April (https://www.worldweatheronline.com/mutoko-weather-averages/mashonaland-east/zw.aspx).

3.3 Methodology Flowchart

The flow chart for the execution of hydrological analysis to generate TWI is given in figure 2 below.

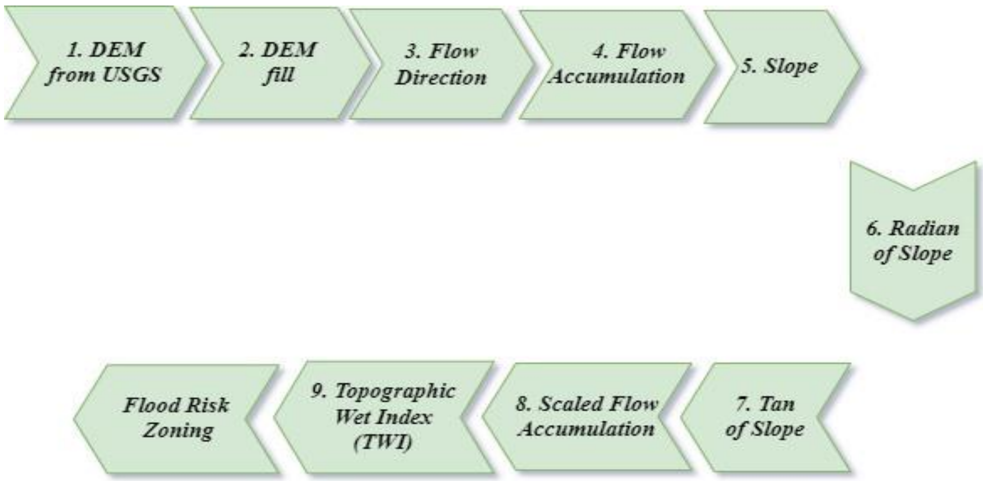

Figure 2: Methodological Flow Chart

3.1 DEM from USGS Earth Explorer

The most widely available DEMs are downloaded from the US Geological Survey (USGS). They are generated using elevation data derived from existing contour maps, digitized elevations and photogrammetric stereo-models based on aerial photographs and satellite remote-sensing images (Garbrecht & Martz, 1992). Two SRTM satellite images from USGS (table 1) were mosaicked and clipped to the study area polygon to create DEM for the study area.

Image ID	***Publication Date***	***Resolution***	***Coordinates***
SRTM1S18_E031V3	23 September 2014	1 Arc Sec	-18, 31
SRTM 1S18_E032V3	23 September 2014	1 Arc Sec	-18, 32

Table 1: DEM images downloaded from USGS (https://earthexplorer.usgs.gov/)

ArcGIS 10.8 desktop was used to perform hydrological modelling from DEM. Spatial analysis tool was used to generate fill, flow direction, flow accumulation and slope maps. Raster calculator from the map algebra algorithm was used to generate radian of slope, tan slope, flow accumulation scaled and TWI.

4. Results and Discussion

4.1 Flow Direction

Flow direction tool determines the direction of flow from each cell to its steepest downslope neighbor. The fill tool was used to fill sinks to remove imperfections from the DEM. The sink spatial analyst tool was used to identify sinks and their depths. To determine flow direction, DEM filled was used as input raster and a flow direction map was generated.

4.2 Flow Accumulation

In this study, flow accumulation helped in generation of stream network. The cell values with zero or lower value represent ridges, while cells with higher values imply accumulation and may represent stream .

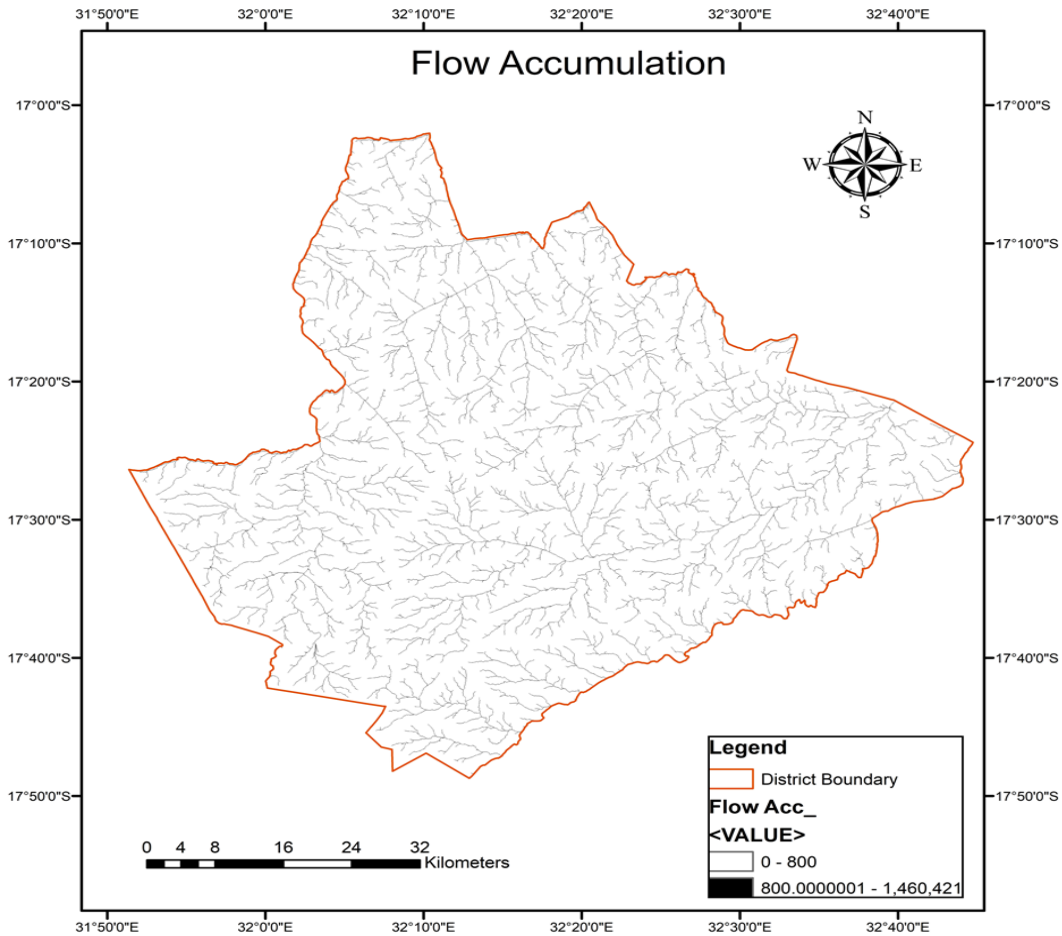

Figure 3: Flow Accumulation map for the study area, generated using ArcGIS 10.8

4.3 Slope

Slope tool in ArcMap was used to identify gradient or steepness from each cell of a raster. Planar method was used with output measurement in degrees. The Z-factor units of the output geographical spatial reference, with *Z-factor of 2* (Z unit as meter).

4.4 Radian of Slope

The radians of a slope refer to its angle or gradient measurement. In this study, raster calculator was used to build and execute a single map algebra expression using python syntax in a calculator interface as shown in figure below, given by: ***Radian of a slope = (slope in degree, 1.570796)/90***

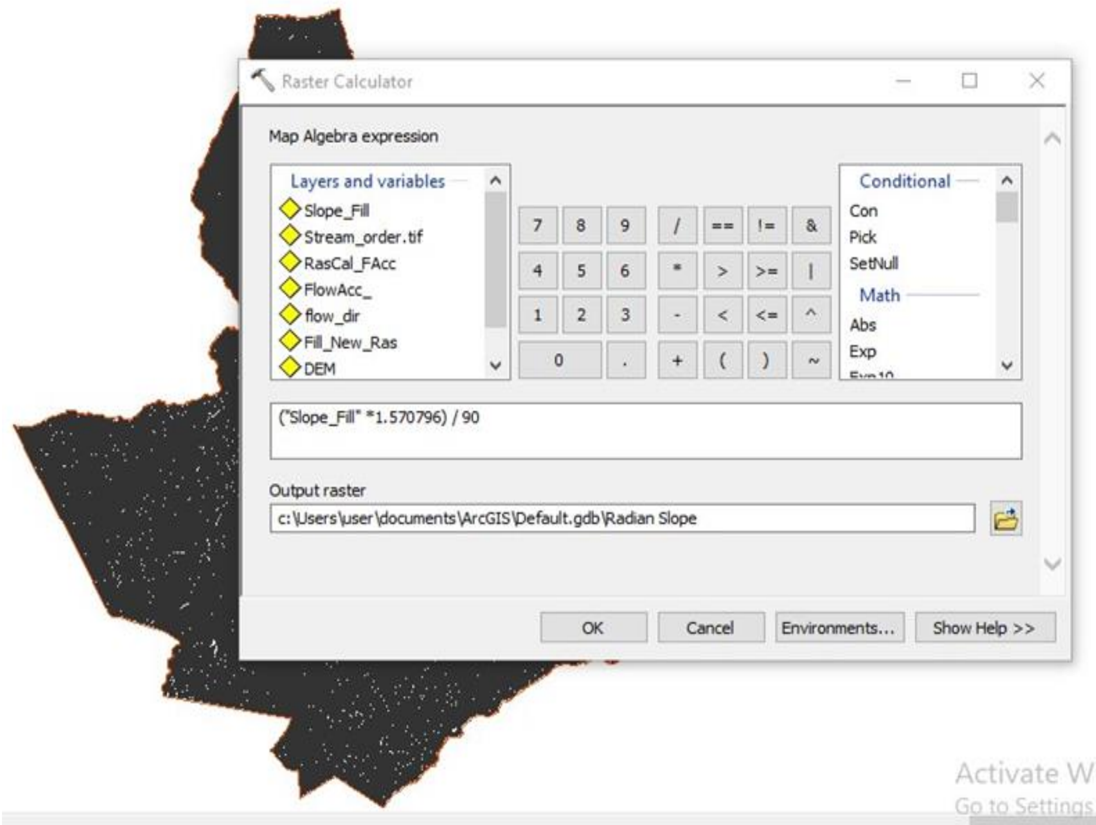

Figure 4: Radian of slope Calculations in ArcMap 10.8

4.5 Tan Slope

Tan slope calculation defined by: ***Tan slope = con (Radian slope >0, Tan (Radian slope), 0.001)***, was used to generate tan slope map. Lower values are common on the Southern part of the district

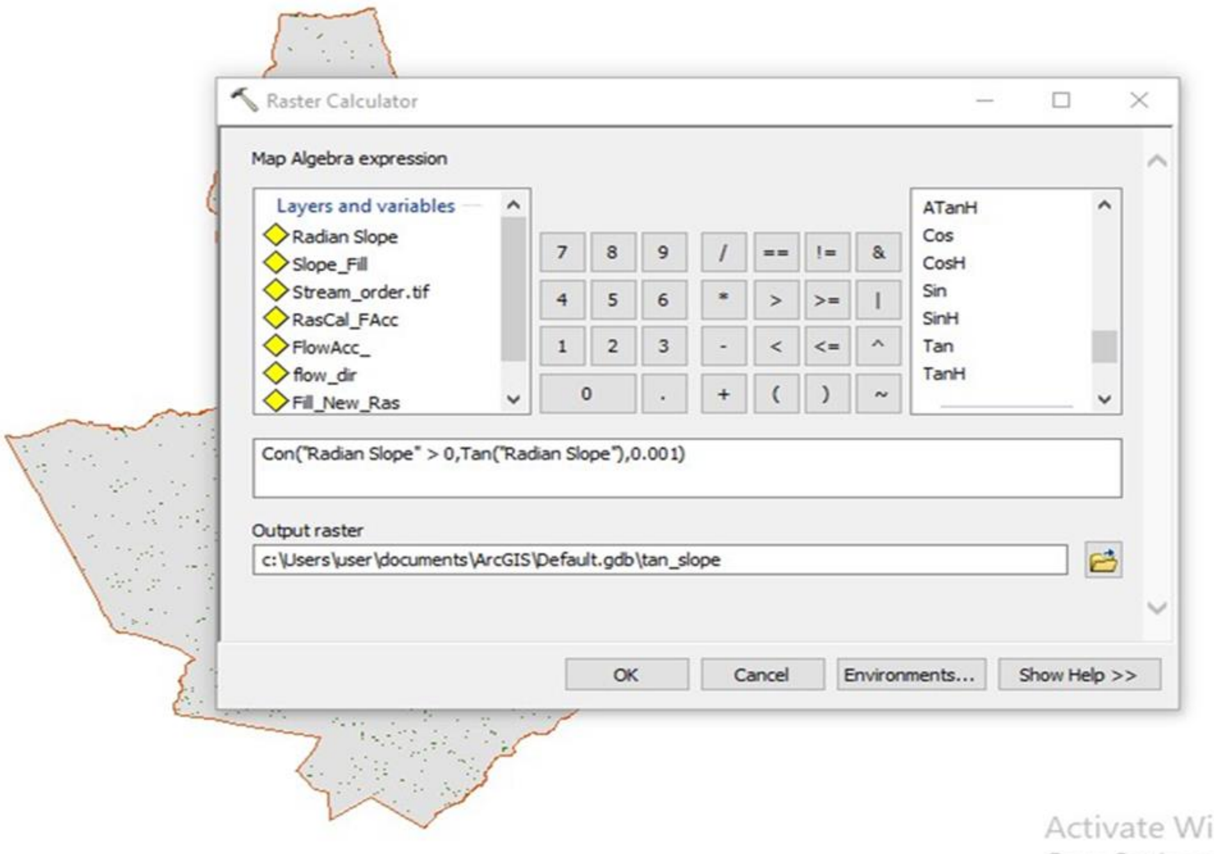

Figure 5: Tan slope Calculations in ArcMap 10.8

4.6 TWI

The TWI method mainly focused on the upper slopes and lower slopes to assess the trend of water accumulation in a region. TWI calculations were based on the topography of an area represented by DEM (Digital Elevation Model) data in the form of DTM (Digital Terrain Model). The high value of TWI is -1.20611 and is associated with high flood vulnerability, whilst lowest TWI value of -8,90624 is associated with low flood vulnerability. Based on the calculation of TWI value, flood-prone areas in Mutoko District include covers the southern and western part of the district as shown in figure 11. The TWI was generated using Map Algebra, utilizing raster calculator, given by:

TWI = Ln (flow accumulation Scaled/Tan Slope)

Flow Accumulation Scaled was derived using raster calculator, given by:

(Flow Accumulation + 1) * 0.00027774796*, with 0.00027774796 as pixel size (x, y) and number of bands as 1.*

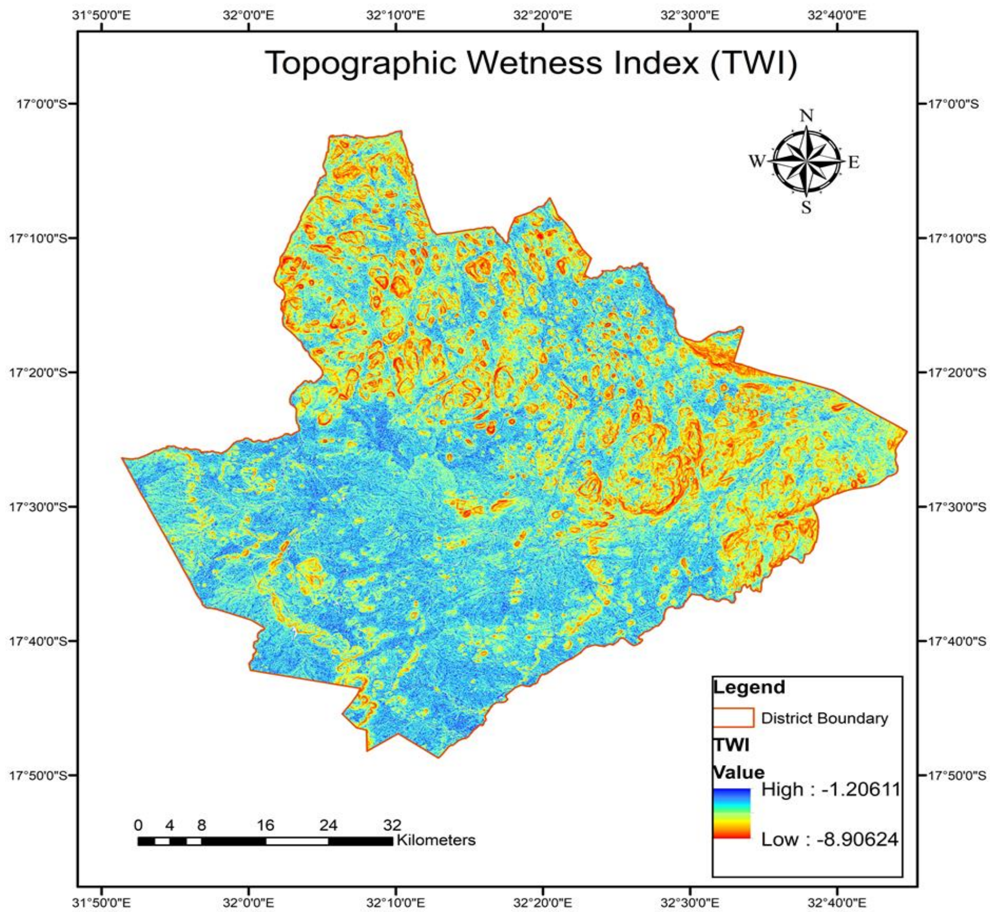

Figure 6: TWI map for the study area generated using ArcGIS 10.8

From figure 6 above, TWI layers are displayed with colour scheme indicating areas with less wetness in brown and areas with high wetness in blue. The other colour illustrating TWI in the study area is yellow, indicating lack of wetness.

4.8 Flood Risk Map

The flood potential zones in Mutoko District derived from TWI calculations are namely; low flood risk, moderate and high flood risk zones. As such, the higher the TWI, the higher the likelihood that the area is prone to flood risks, while areas with low TWI resemble low flood risk areas. From figure 7 below, the flood risk map for Mutoko District was derived from TWI calculations.

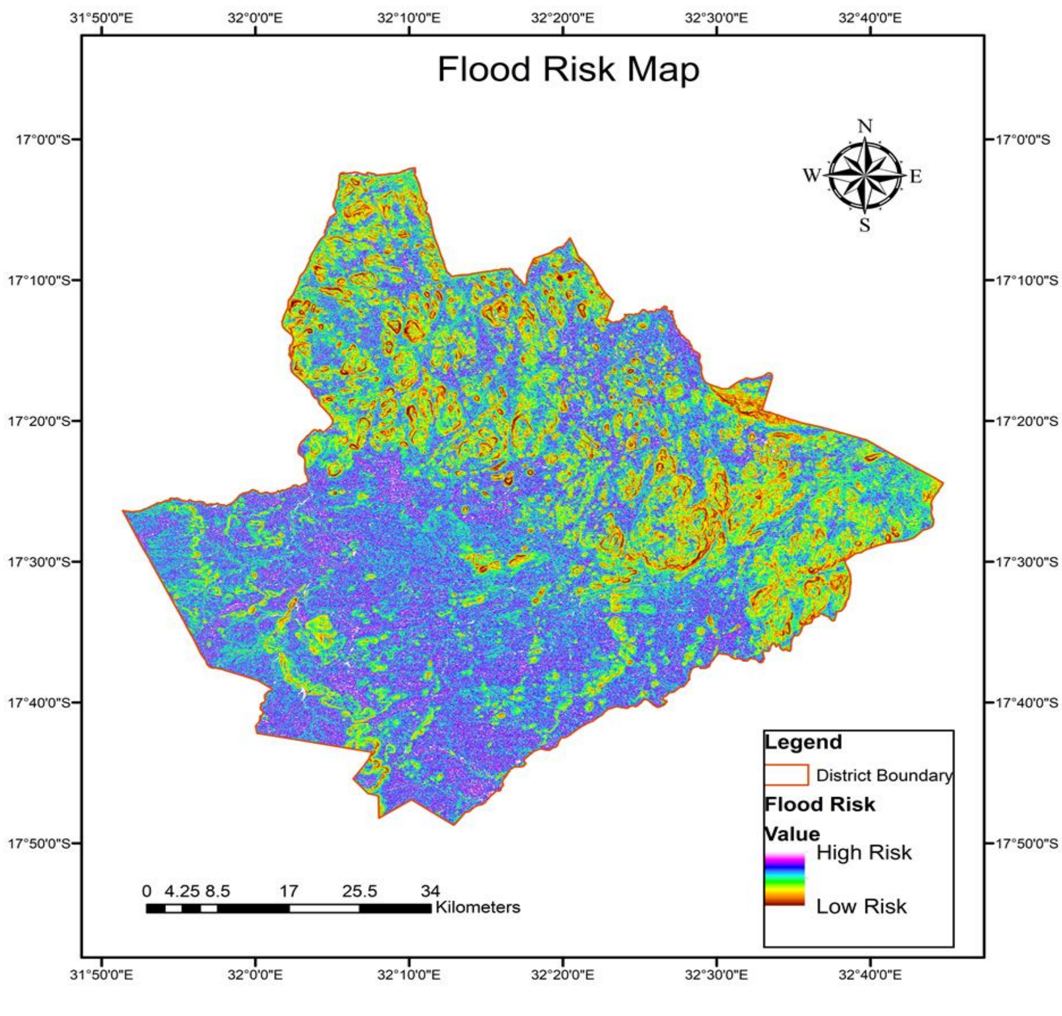

Figure 7: Flood Risk Potential Map for Mutoko District (based on TWI calculations)

TWI calculations help to generate flood risk maps which help District Administrators, Government ministries in decision making with regards to emergency preparedness, utilizing both climatic data and TWI to allocate resources.

5. Conclusion and Recommendations

The flood potential zones in Mutoko District derived from TWI calculations are namely; low flood risk, moderate and high flood risk zones. As such, the higher the TWI, the higher the likelihood that the area is prone to flood risks, while areas with low TWI resemble low risk areas. Given that the TWI concept is less suitable in flat areas due to undefined flow directions which are more likely to change over time (Grabs et al., 2009), Mutoko District was chosen for this study due to variation in topography in the region. Though the index help to quantify topographic control on hydrologic processes and terrain driven variation in soil moisture, it is also highly correlated with several soil attributes such as horizon depth, silt percentage, organic matter content and phosphorous. Though TWI utilizes topographic elements of landscape to determine water flow and accumulation, additional information at micro scale such as soil type or rainfall, would be necessary for comprehensive hydrological modelling and flood risk mapping. Availability of meteorological and hydrological data in addition to a digital elevation model (DEM), provides a more dynamic approach for comprehensive analysis, allowing dynamic simulations of spatially distributed water storage that can be used to derive alternative wetness indices.

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Potential Competing Interest

No potential competing interests to declare.

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