International Journal of Advanced Technology & Engineering Research (IJATER)
www.ijater.com

USING A GIS-BASED MODEL AS A DECISION SUPPORT FRAMEWORK FOR IDENTIFYING SUITABLE RAIN WATER HARVESTING SITES

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Abstract

This research uses a GIS-based model as a decision support framework to optimize and identify locations to implement Rain Water Harvesting (RWH) management strategies effectively and efficiently. Rainfall, soil texture, DEM, slopes and land use/land cover were used as model development indicators. These indicators were rasterized and reclassified unto a five class digital number range for raster interpolation. Project findings indicates that, GIS-based model for identifying the suitable RWH potential sites could be customized, interpolated and predicted based on percentage influence preference scales of each RWH indicator. In addition, a sensitivity analysis on percentage influence was conducted to provide an insight into the influence of each RWH indicator in weights assigned to each indicator. Suitability classes developed indicated that, with a 25% influence of each RWH indicator as a control, rainfall was the most important indicator for identifying a RWH potential site. Its significant increase was proportional to increased percentage influence followed by soil indicator. Due to the location of research site, slope map generated from DEM contributed less in RWH suitability maps and was inversely proportional to increased percentage influence. However, the south western boundaries indicated higher RWH potentials whilst the northern, poor to not suitable potentials. In view of these, research outputs presented a guide to policy formulation and information for policy makers in terms of resource allocation at basin scale for sustainable wide scale adoption of RWH potentials in the White Volta Basin. As such, water resource management strategies to make water available for irrigation measured could be adopted in water stressed seasons of the northern part of the country, thereby increased agricultural productivity.

Keywords: Harvesting, Rainwater, GIS, Remote sensing, Decision support framework, Modeling

Introduction

The Northern part of Ghana where the White Volta Basin lies is under continual pressure due to continual farming intensification, land use change, deforestation and scares water situations [2, 18, 22]. Governmental organizations still build capacities and its associated interventions in most water related activities, yet their capacity still remains inadequate [25]. As defined by Satya [36] RWH is the technique of collecting and storing rain water at surface or sub-surface aquifers, before it is actually lost as surface run-off and despite multiple measures, there is continual reluctant of adoption of RWH techniques. In addition, population growth and change in climatic variables [24, 31], compounds the issues associated with water resources. Rainwater harvesting potentials offers unlimited effects in mitigating the effects of water scarcity [21, 26].

Water resources are gradually becoming an acute resource in the ecosystem which serves as a reservoir for living organisms and the food basket in the Northern part and Ghana as a whole [4, 14]. Many scientists [10, 20, 29, 36] have research into the development of decision support systems for identifying potential sites for rainwater harvesting. RWH which is significant in domestic usage [1, 35] is thus a simple and affordable technique for augmenting groundwater table [36]. Cities such as Japan, London, and Melbourne have implemented and adopted large scale rainwater use in public facilities [11, 27, 28].

About 54.7% of the White Volta Basin catchment constitutes small pots of rainfed agriculture [5, 17]. Thus bridging the demand and supply gap in crop production and other use of water resources in agriculture abhors as irrigation farming in the dry season supports crops (such as tomato, onion, pepper etc.) production. This papers develops a GIS-based model for for Identifying Potential Sites for Rainwater Harvesting

GIS-based Model for RHW.

The methodology use to determine the potential RWH site for the study area using GIS and remote sensing is indicated in the flow chart in Figure 2. The decision support system (DSS) for identification of potential sites for RWH was implemented in ESRI ArcGIS.

Study Area

The White River Basin is located in the Northern part of Ghana in the interior savanna agro-ecological zone (shown in Figure 1). The area lies between latitude 2^{O} 30’ W and 0^{O} 30’ E and longitude 11^{O} 30’ N and 8^{O} 30’ N with a geographical area of approximately 37.44 sq Km. Alternate water sources used in the study area include borehole and shallow wells; however, these are prone to contamination [7].

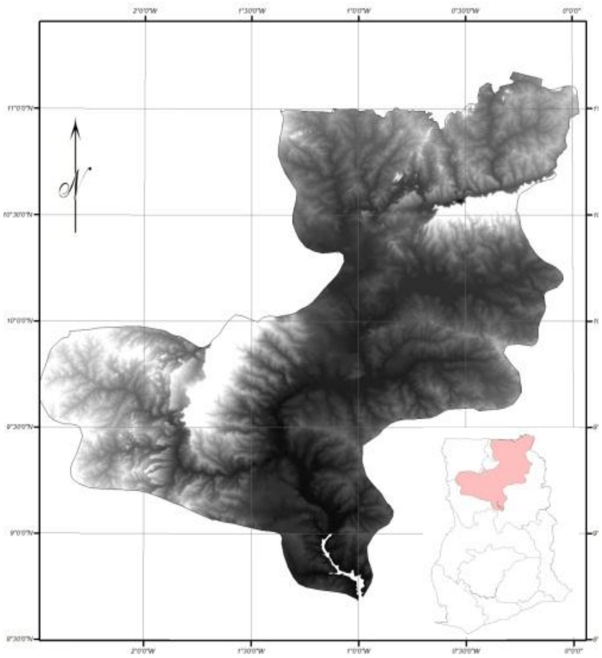

Figure 1: Map showing the study area

Data Source and Preparation

Datasets used in the study are: digital soil map, Digital Elevation Model (DEM), land use/cover map, and an existing rainfall map. These were obtained from the developed geodatabase of the CSIR-Soil Research Institute. The soil data (as can be seen in Figure 3a) mapped over the years was reclassified into five classes based on the FAO soil classification scheme [33]. The encountered classified soil orders were leptosol, plinthosol, planosol, fluvisol, acrisol, luvisol, lixisol, vertisols and gleysols.

DEMs, which were developed based on the 50feet grid contour interval, were used for the analysis of topography as well as modeling of surface processes. In this research, a DEM of the study area was generated in ESRI ArcGIS software. Detailed information on DEMs data formats, interpolation techniques, and accuracy assessment of DEMs can be found in Forkuo [12].
Slope map in Figure 3b was developed from the generated DEMs. As can be seen in this Figure, slopes were reclassified into 5 classes [9].

An Aspect map was also generated to aid in flow analysis. In addition, to obtain the land use/cover map of the study area satellite image was classified. A total of five classes were selected upon prior field investigations. The image was taken through four stages to generate a land cover classes of the study area. These include: image pre-processing; feature extraction; selection of training data (signatures); and selection of suitable classification approaches. The following five land use/cover classes were obtained: non-biotic constructed area, arable/agricultural lands, savanna lands, water bodies, and others. After the classification, sample points were obtained from the field for accuracy assessment. The image classification was guided by reconnaissance information gathered from the field of the study area and a classification accuracy assessed from the error matrix. Figure 3c shows the classified image with five classes. Detailed information on land cover and use classification, supervised classification techniques, and classification accuracy assessment using error matrix can be found in Forkuo and Adubofour [13]. The rainfall datasets observed in the area ranged from <640mm to >1000mm as shown in Figure 3d.

Weighted Overlay Analysis

The purpose of the weighted overlay analysis is to apply a common scale of values to diverse and dissimilar data input to create an integrated analysis [23]. ESRI AGIS is used to implement Weighted Overlay Analysis. The weights calculated for each factor using

$$S = \sum Zi * Xj \qquad (1)$$

where Zi is the weight of indicator i and Xi is the criteria score of the indicator I [3, 15]. To finally classify RWH indicators into combined weighted overlays [32], suitability classes were scaled from 1 to 5 (not suitable, marginally suitable, moderately suitable, suitable and highly suitable). RWH suitability classes of different measurement units needed to be standardized as different constraints existed with different indicators. Thereon, one way ANOVA analysis was used to analyse the percentage influence of RWH indicators on RWH potential sites. The combined analysis showed that rainfall followed by soil were the only indicators that significantly changed the geographical extent of potentials for RWH in the basin [15].
This indication guided the development of conditions to be used in the weighted overlay analysis as shown in the Table 2.

Table 1: Development of 5 suitability class

RWH Indicators	CLASSES				
	Not Suitable	Marginally Suitable	Moderately Suitable	Suitable	Highly Suitable
	1	2	3	4	5
Landuse	Non-biotic constructed area	Others	Agricultural lands	Savanna Lands	Water Bodies
Rainfall	<640	640-790	790-900	900-1000	>1000
Slope	>30	14-30	8-14	2-8	<2
Soil	Leptosol	Plinthosol	Planosol, Fluvisol	Acrisol, Luvisol, Lixisol	Vertisol, Gleysol

Table 2: Applied percentage influence (weights) of each RWH indicator

RWH Indicators	Conditions				
	I	II	III	IV	V
Landuse	25	20	15	15	10
Rainfall	25	30	40	30	50
Soil	25	30	30	40	30
Slope	25	20	15	15	10

With the conditions stated in Table 2, percentage influence of RWH indicators were further correlated on a bar graph as percentage influence against condition (in this case, based on RWH indicators). That is Figure 4 shows the percentage (%) influence of RWH indicators.

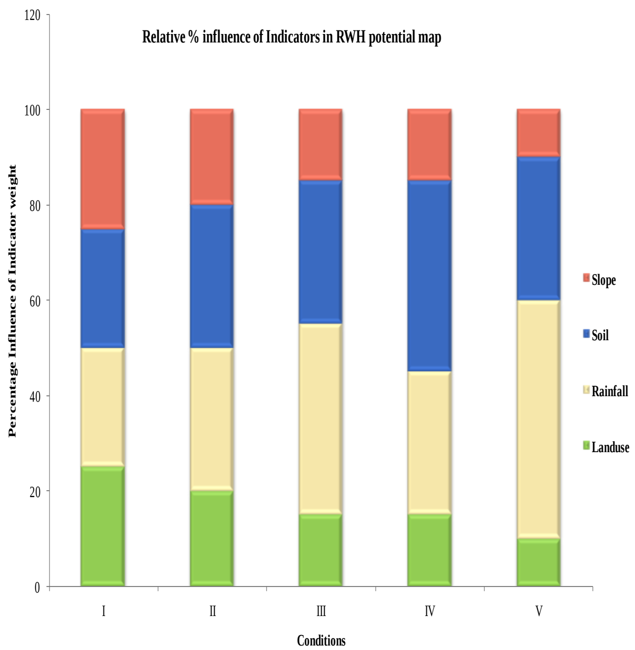

Figure 4: Conditions of applied percentage influence (weights) in each RWH indicator

Results and Analysis

In this study, the input layers in the form of vector maps were rainfall, slope, soil texture, and land use/cover. The relative importance of each layer in selecting potential sites for RWH has been analysed.

Percentage Influence of RWH Indicators

The percentage influence of RHW indicators were used in generating five scenarios using five different conditions in Table 2. The values of the first scenario were used as control test (or scenario 1). An equalization control percentage (25%) was applied to each RWH indicator to generate the potential map in Figure 5a. Figure 5b also shows the percentage influence of this control test (i.e., the extent of RWH). This potentiality shows that about 55% of the control test was moderately suitable and about 30% marginally suitable.

In modeling the second scenario using the second condition, weights applied as percentage influence of indicators was changed; land use, from 25 to 20, rainfall, 25 to 30, soil, from 25 to 30 and slope, from 25 to 20. Slope was reduce because the DEM model developed shown a uniform and un-dissecting topography of the area.

With these changes in the percentage influences, there was a 2% change in the extent of suitable areas with about 3% increase in marginally suitable areas and Figures 6a and 6b show the results of modeling scenario 2.

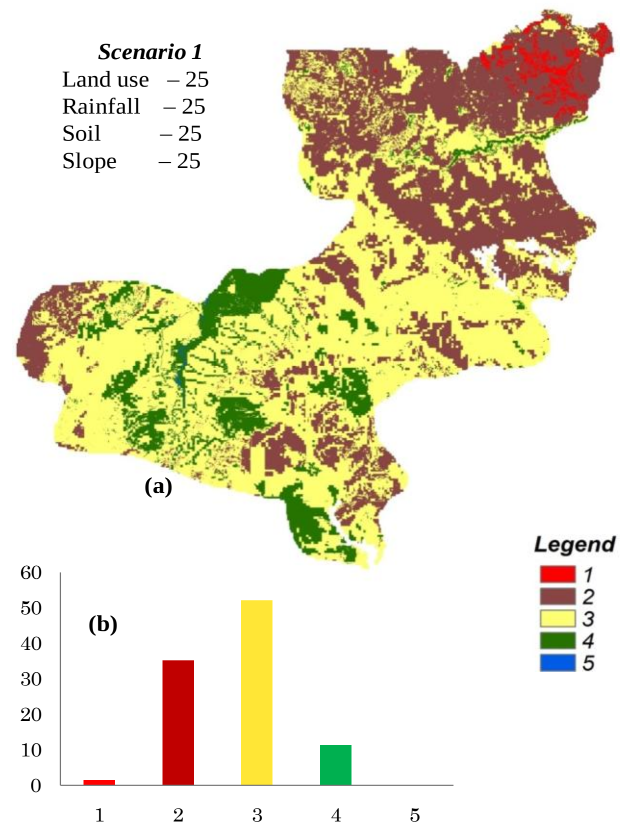

Figure 5: a) Map showing results of Scenario 1, b) percentage influence of Scenario 1

As can be observed, rainfall and soil were the most contributing factors in identifying the potential areas (in relation to the study area). With this indication, weights applied to indicators were further increased and others decreased in modeling the third scenario (i.e.; land use, from 20 to 15, rainfall, 30 to 40, soil, still at 30 and slope, from 20 to 15). These changes graphed in Figures 7a and 7b.

It could be seen that the increased 40% weight influence further increased the geographical extent of suitable areas from 12% to 18%. However, the area classified as not suitable, increased. This showed that, an increase in weight applied to rainfall with no increase in applied weight to soil was not appropriate, hence the need to develop condition 4

Similarly, modeling the fourth scenario, weights of land use was maintained at 15% influence, rainfall, reduced to 30%, soil, increased to 40% and slope, maintained at 15%. With these changes, 25% gap interval between moderately suitable areas and marginally suitable areas narrowed to about 5% (as shown in Figure 8a).

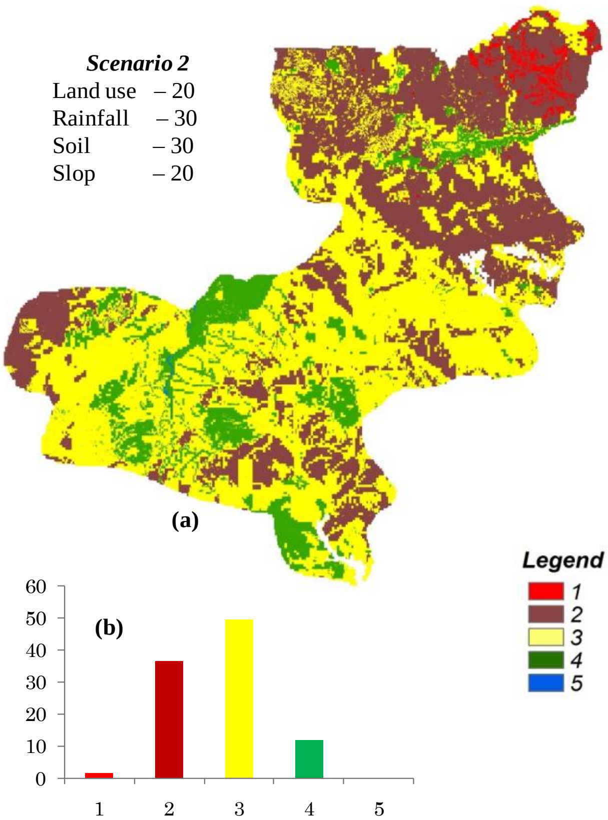

Figure 6: a) Map showing results of Scenario 2, b) percentage influence of Scenario 2

This indicates that, an increase in weight influence in soil with a corresponding decrease in rainfall weight influence was not prudent. Moreover, the extent of not suitable classified areas was shown to be gradually increasing (as shown in Figure 8b).

Finally, there was a trend indication that, any increased in applied weight influence in to rainfall indicator resulted in an increased geographical extent of potential RWH sites. Hence, in modeling the fifth scenario, weights of land use was reduced to 10% influence, rainfall, increased to 50, soil, maintained at 30 and slope, reduced to 10 as shown in Table 2 and the results are shown in Figures 9a and 9b.

It could also be seen that areas classified as not suitable decreased, followed by marginally suitable areas. The 25% loss of extent under condition 4 was regained under condition 5 with a corresponding increase in areas classified as suitable and highly suitable. This scenario was the only model that resulted in almost 5% increase in highly suitable classified areas in the study area.

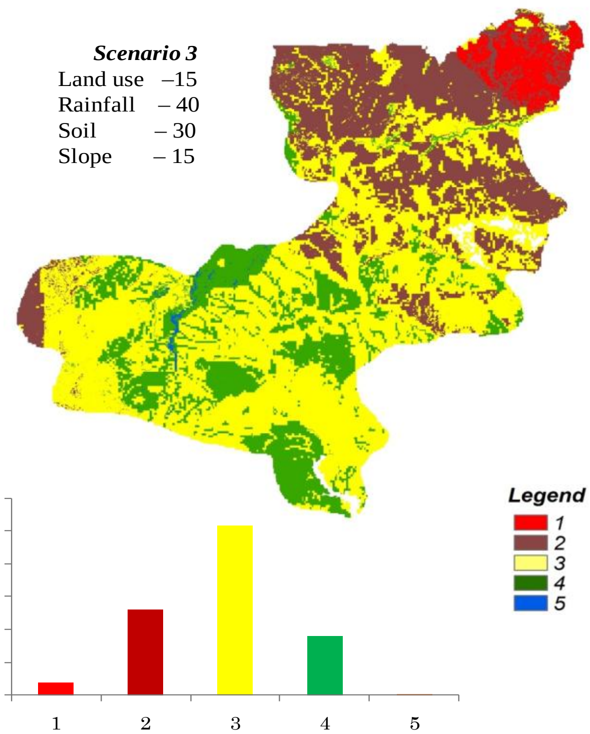

Figure 7:a): Map showing results of Scenario 3, b) Percentage influence of condition 3

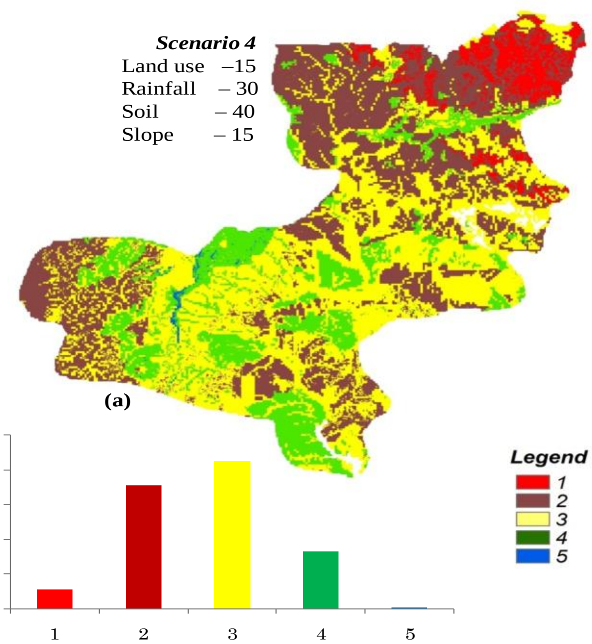

Figure 8: a) Map showing results of Scenario 4, b) percentage influence of Scenario 4

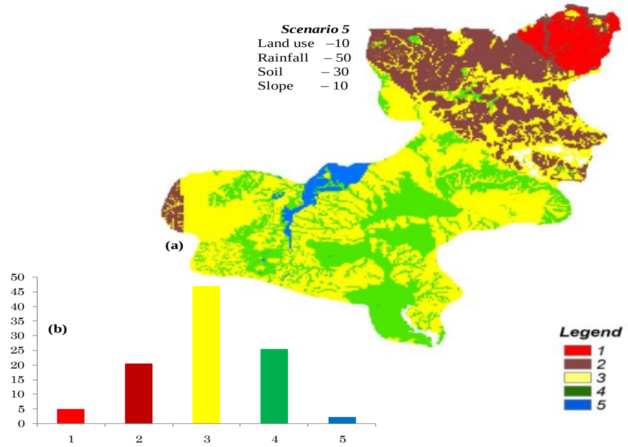

Figure 9: a) Map showing results of Scenario 5, b) percentage influence of Scenario 5

Assessing the Residual Effects of Percentage Influence of RWH Indicators

To remove data trend and analyze indicator residuals [30, 35] there was the need to apply raster subtraction to the developed surfaces obtained from the 5 modeled conditions. Condition 1 as the control test with equal percentage influence, each other condition model was subtracted to obtain the residual effects of percentage influences [19, 32]. Differences in % influence of RWH indicators was re-classed into 3 classes (ranging from high potential (-1), medium potential (0), low potential (1)).

Model 1: Scenario 1- Scenario 2

The percentage Influence Difference between scenario 1 and 2 was analyzed and the results are shown in Figures 10a and 10b. That is scenario 2 (percentage influences; land use, 20, rainfall, 30, soil, 30 and slope, 20) was subtracted from the control test (i.e., scenario 1). This evaluation indicated that, 90% of the potential sites were within the medium potential range as compared to the high and low potential range.

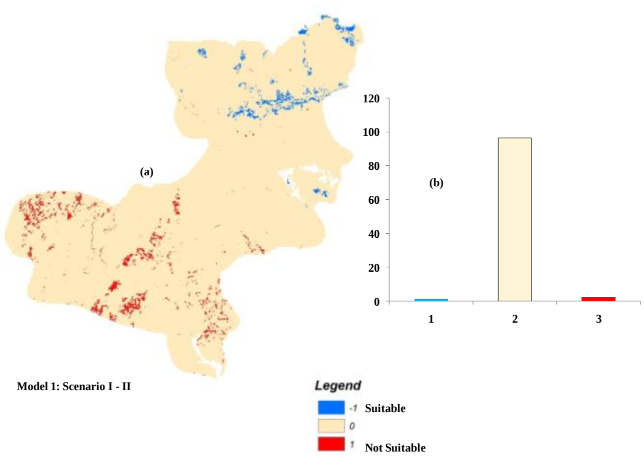

Figure 20: a) Map and b) Chart showing results of Model 1

Model 2: Scenario 1- Scenario 3

As in Model 1 and 2, model 3 (Figures 11a and 11b) shows the results of raster subtraction of scenario 3 (percentage influences; land use, 15, rainfall, 40, soil, 30 and slope, 15) from the control test. What is the most evident about this model is that 80% of the potential sites were within the medium potential range, 16% in the high potential zone and 4% in the low potential range.

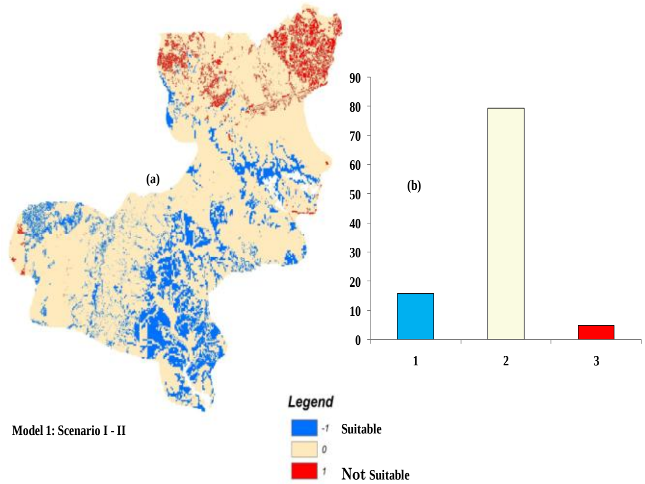

Figure 113: a) Map and b) Chart showing results of model 2

Model 3: Scenario 1- Scenario 4

However, in model 3 where scenario 4 was subtracted from the control test, the extent of coverage, covered by the low potential range increased to 10% (as shown in Figure 12a and 12b). This was an indication that soils in the project area had less influence in the estimation of potential sites as compared to increased rainfall influence.

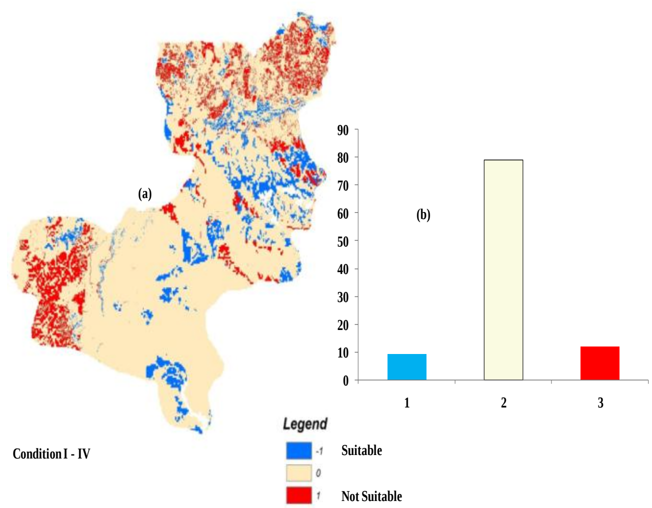

Figure 4:a) Map and b) Chart showing results Model 3

Model 4: Scenario 1- Scenario 5

Furthermore, to really confirm the continual weights increase assigned to rainfall, condition 5 was also subtracted from the control test. This further showed that (as shown in Figure 13a), 35% of the study area was within the high potential range with decreased in the extent of medium potential sites (60%). Figure 13b shows the occurred change.

The four models were integrated and the final integrated model which was adopted is shown in Figure14. This clearly gives an indication of which indicator contributed the most in identifying the potential sites.

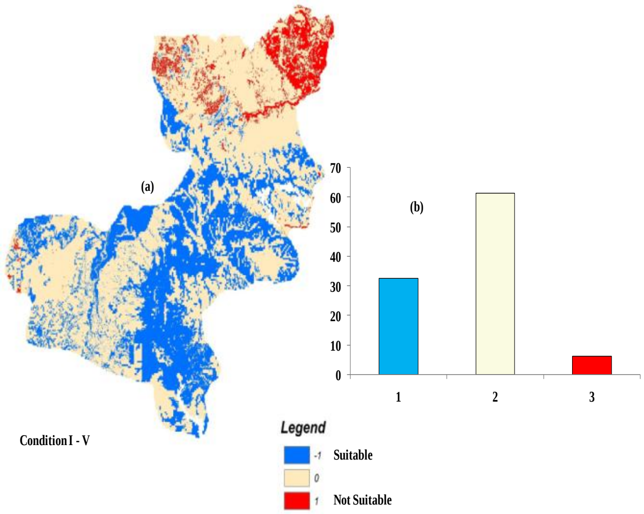

Figure 13: a) Map and b) Chart showing results Model 4

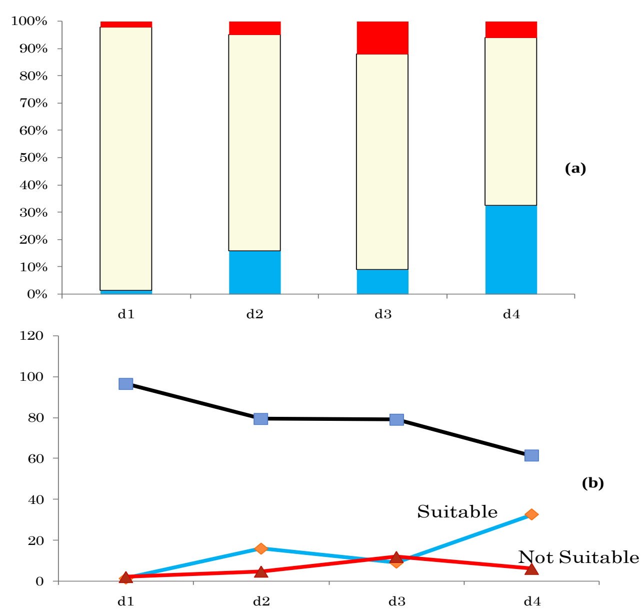

Figure 14: Graphical representation of the 4 models adopted

Conclusions and Recommendations

The south western boundaries indicated higher RWH potentials whilst the northern, poor to not suitable potentials. Outputs of results were dependent on rainfall amounts or intensification. Research outputs presented a guide to policy formulation and information for policy makers and In terms of resource allocation at basin scale for sustainable wide scale adoption of RWH potentials in the White Volta Basin. Water resource management strategies to make water available for irrigation measured could be adopted in water stressed seasons of the northern part of the country, thereby increased agricultural productivity. The model used is only valid for this type of relation. However, it does not deny the possibility of other kind of relations within our study system. In this regard, the modeling approach should be considered as a guide in identifying essential interactions on which empirical efforts should be targeted to confront the results obtained with purely observational approaches such as that employed in this study. Other RWH technology devices should be studied for adoption in such RWH potential sites.

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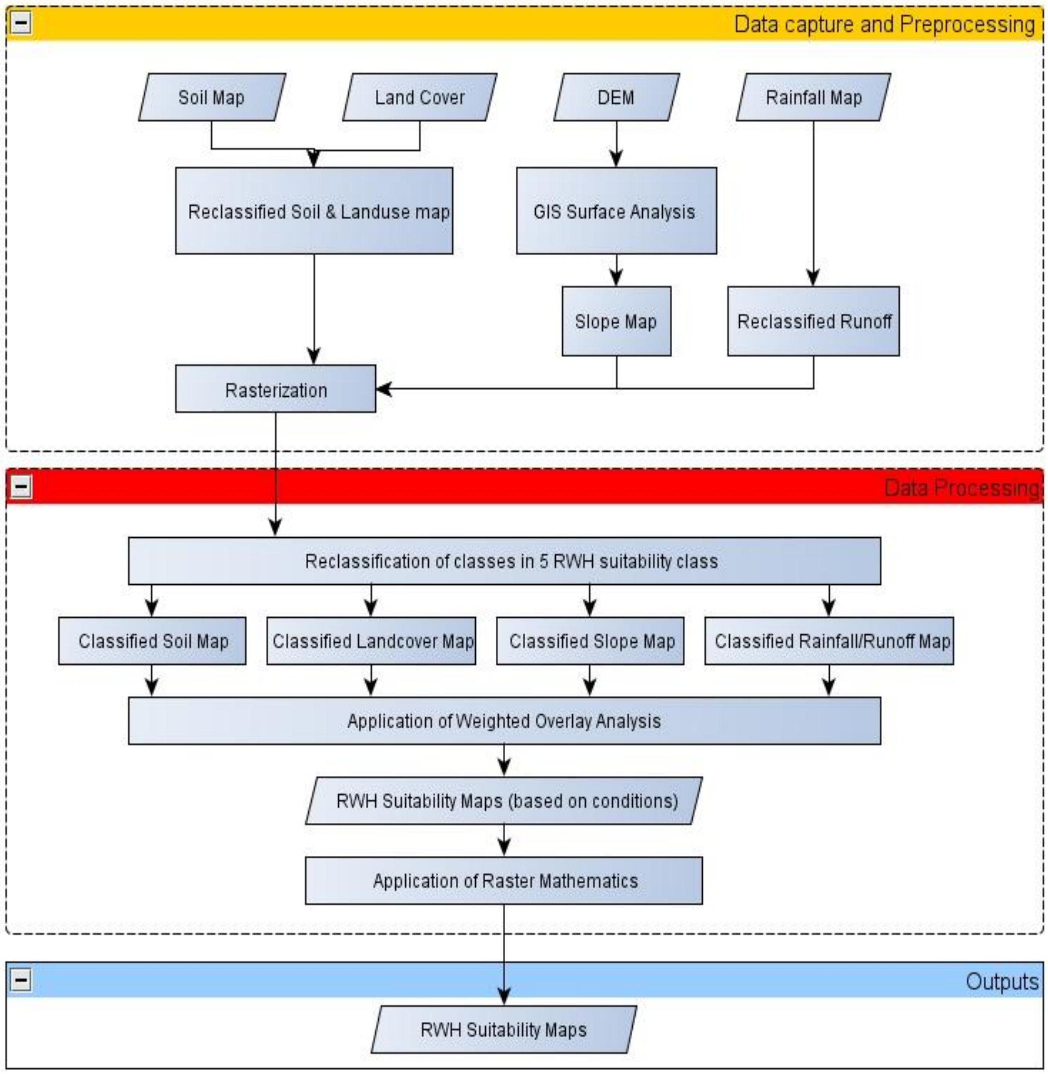
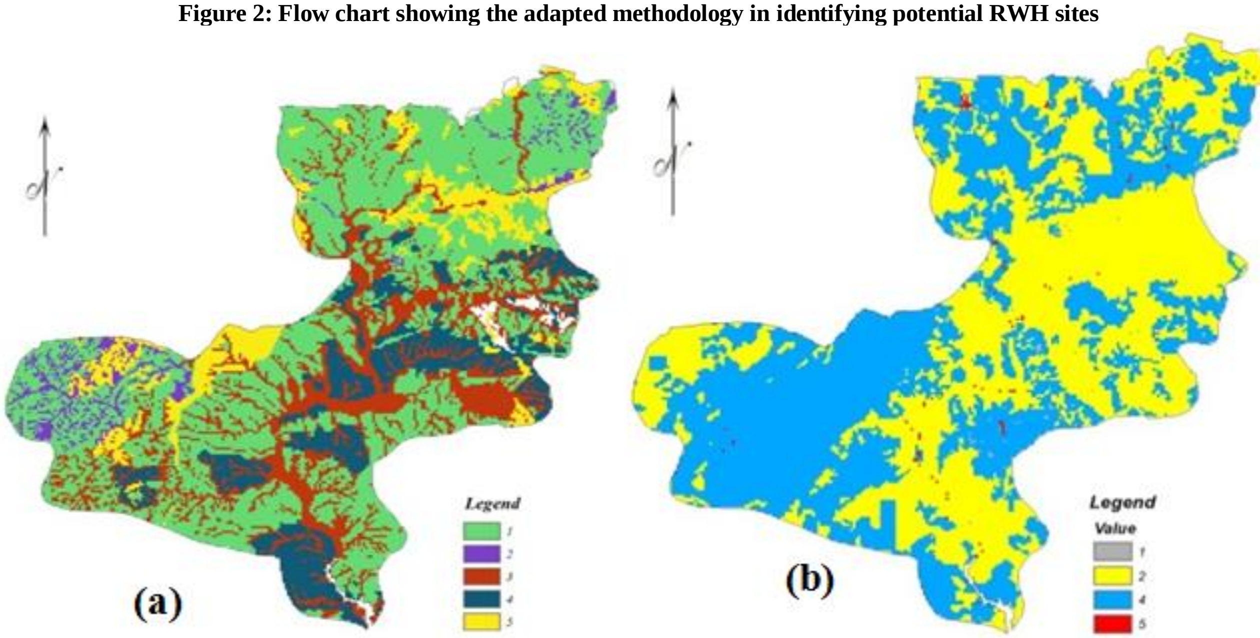


Figure 2: Flow chart showing the adapted methodology in identifying potential RWH sites



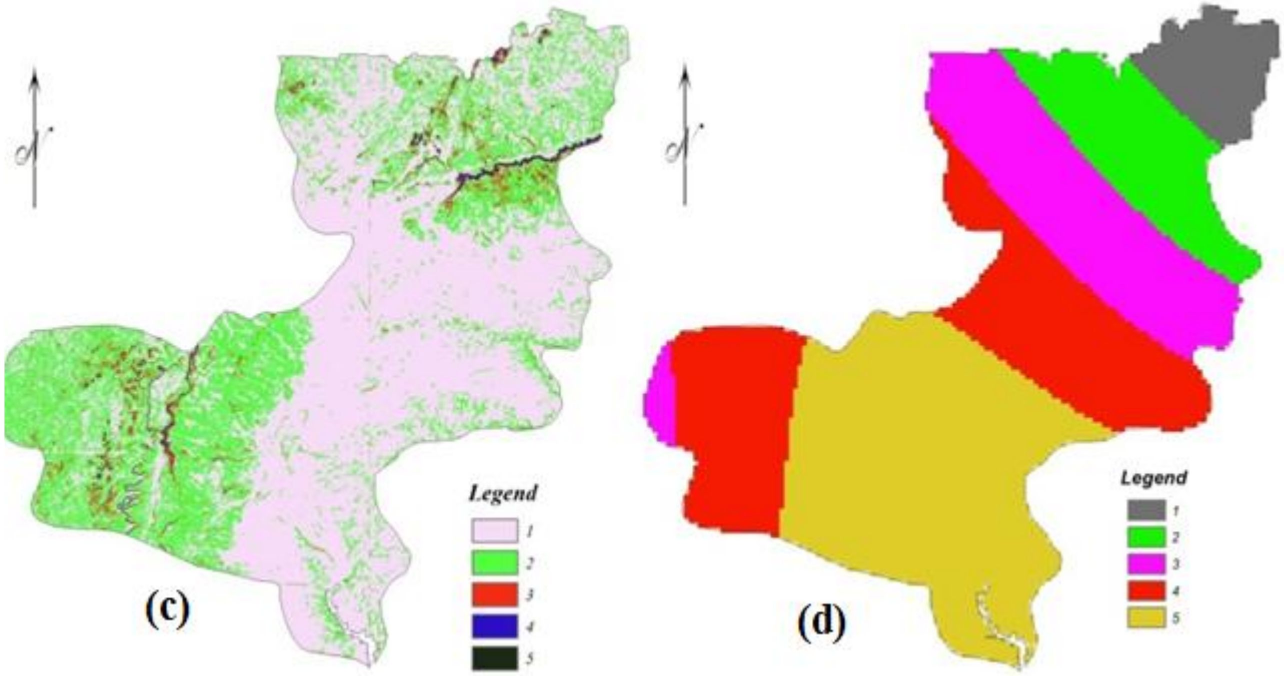


Figure 3:a) soil map of the study area reclassified into 5 classes, b) slope map generated from the DEM, c) landuse map of the study area in 5 classes, and d) rainfall distribution map of the study area