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Mapping potential areas in the upper west region of Ghana for the implementation of agricultural water management: GIS and remote sensing approach

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Abstract

Potential areas for the use of Small Reservoirs and Stone Bunds as agricultural water management interventions have been assessed using Weighted Overlay Analysis (WOA). The four key parameters that were combined to obtain the suitability levels of the interventions are runoff, soil type, land use/cover and slope. The results indicate high potential areas of 57.25% and 85.40% for small reservoirs and Stone bunds respectively. Comparing the two interventions in terms of slope suitability, the high potential areas for small reservoirs occurred on undulating slopes (0-8%) and that of the stone bunds on rolling slopes (8-16%). Luvisols and nitosols were identified by the model to be the soil types that support the use of small reservoirs and stone bunds in the high potential areas. A validation of the results revealed that 65.15% of existing small reservoirs in the study area were located in areas predicted by the model to be of high potential.

Keywords: Small Reservoirs; Stone bunds; Potential areas; GIS.

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1. Introduction

In many developing countries, water remains a major constraint for increasing agricultural output especially during the dry season. As such the adoption of Agricultural Water Management Interventions (AWMI) is essential for improving the profitability of smallholder farmers. This could simultaneously reduce poverty, increase food security and help in adapting to climate changes and variability (UNEC, 2011). Some common AWMI include shallow wells, stone bunding, tied ridges and small reservoirs. However, only small reservoirs and stone bunds used as water management interventions for agriculture have been considered by this study. This research brings to the fore how geographic information system (GIS) and remote sensing techniques have been used to identify potential areas where these interventions can be implemented for adoption and scaling-up on the basis of mainly biophysical factors; as well as aid planning and monitoring activities.

Small reservoirs are typically formed by constructing simple earth dams. More often than not, these dams do not have outlets thus water from the reservoir is generally used for livestock watering and pumping for irrigation (Johnson et al., 2010). Stone bunding on the other hand involves lining stones or making stone bunds along a contour. This intervention does not concentrate runoff but spreads it and also reduces the rate of runoff allowing infiltration. The structures for the contour stone bunds are laid to a height of 2.5m with a base width of 3.5-4.0m.To increase stability; the stones are set in trenches of about 0.5-1.0m depth. The stone bunds are usually 1.5-3.0m apart (Ruffino, 2009).

2. Description of study area

The upper west region (UWR) as shown in Figure 1 covers a geographical area of 18,476km^2 which constitutes 7.7% of the total land area of Ghana (MoFA, 2011). It is estimated that about 70% (12,933.2 sq km) of the land size in the UWR is arable. The soil types in the region include Fluvisols, Arenosols or Gleysols which fall approximately under the FAO classification system (MoFA, 2011). The climate is characterized by a short, single-peak rainfall regime and a long dry season from October to the end of April. The UWR can be subdivided into two agro-ecological zones: the Guinea Savanna in the southern part and the Sudan Savanna in the northern and north eastern parts. The population of the region is about 702,110 (GSS, 2010) and about 80% of the economically active population are engaged in agriculture (crop and livestock farming). Crops cultivated in the region include cereals, nuts, tubers and vegetables. However, access to water for domestic purposes, livestock watering, irrigation and fishing is especially difficult during the dry season.

3. Materials and methods

For the purposes of this research, the model builder in ArcGis 9.3 was used. The input parameters into this builder were mainly runoff, soil type, slope and land use or vegetation cover (Prinz *et al*., 1998). For purposes of comparison, the four input parameters (LULC, runoff, soil type and slope maps) were reclassified into five suitability classes namely; optimally suitable (5), highly suitable (4), moderately suitable (3), marginally suitable (2) and not suitable (1). Figure 2 shows the flow chart of how Geographic Information System (GIS) was used as platform for the integration and processing of the various parameters used in mapping the potential areas.

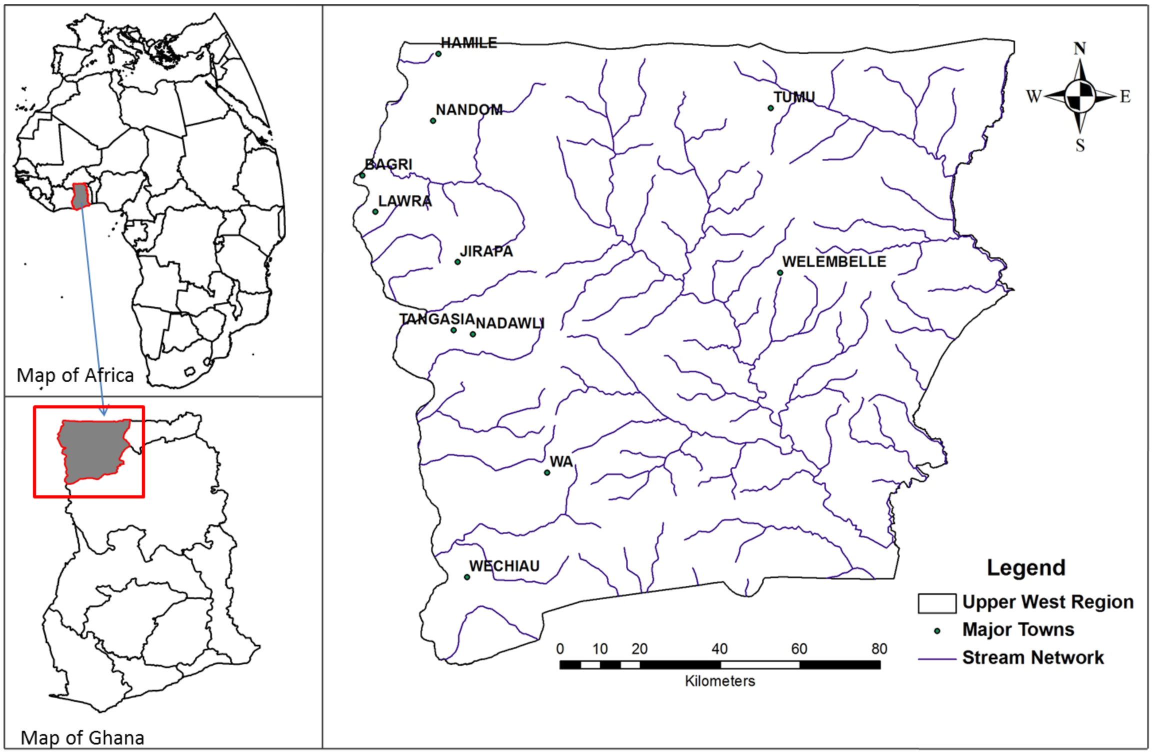

Figure 1. Study area showing major towns and stream network

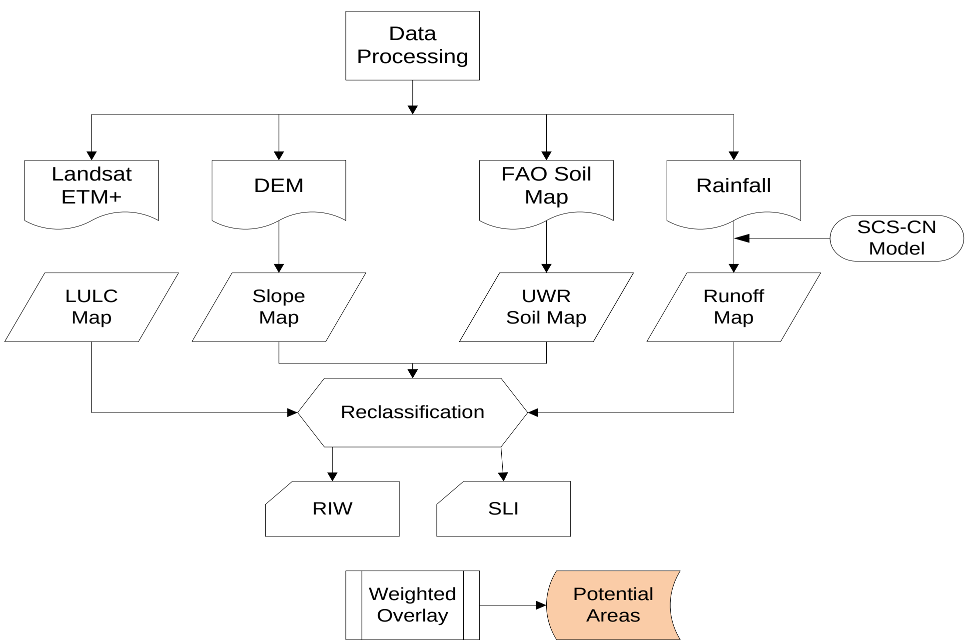

Figure 2. Flow Chart for Identification of Potential Areas for Agriculture

3.1. Land use/cover

The Landuse/Landcover (LULC) was determined through interpretation of aerial photographs of 1983 at a scale of 1: 65,000. Visual interpretation employing size, pattern, texture, shadow, tone and shape (Tumbo *et al*., 2005) were used in identifying the LULC types namely cropland with open woody vegetation, deciduous woodland and deciduous shrubland with sparse trees (Figure 3). Shown in Table 1 are the suitability levels for the landcover types.

Table 1. Suitability Level for Landcover

Landcover Types	Suitability Levels	
	Small Reservoir	Stone Bunds
Deciduous woodland	2	1
Deciduous shrubland	4	3
Cropland	5	5

Adapted from Tumbo et al. (2005)

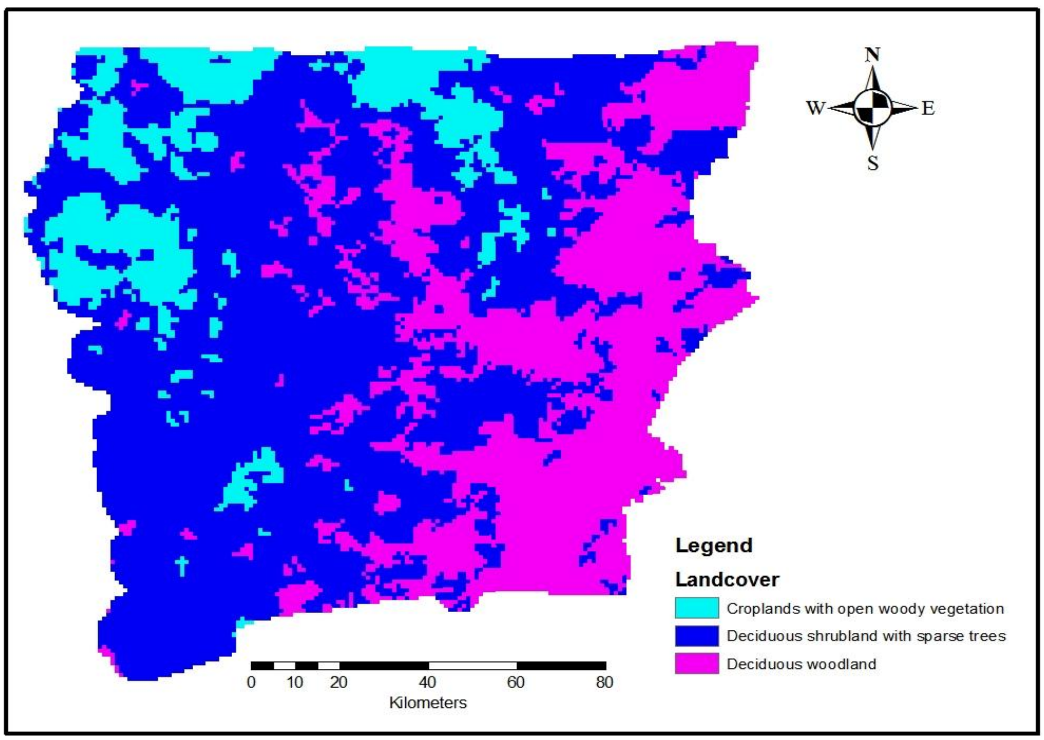

Figure 3. Landcover Map

3.2. Slope

The slope map was generated through the surface analysis operation from the spatial analyst tools using the digital elevation model (DEM) in Figure 4 as the input parameter. The map was then reclassified into five classes (Figure 5) using the classification proposed by FAO (2002) namely: flat (0 – 2%), undulating (2 – 8%), rolling (8 – 16%), hilly (16 – 30%) and mountainous > 30%. The suitability level for slope with regards to small reservoirs and stone bunds is shown in Table 2. The steepness of the slope was used in identifying preferable areas.

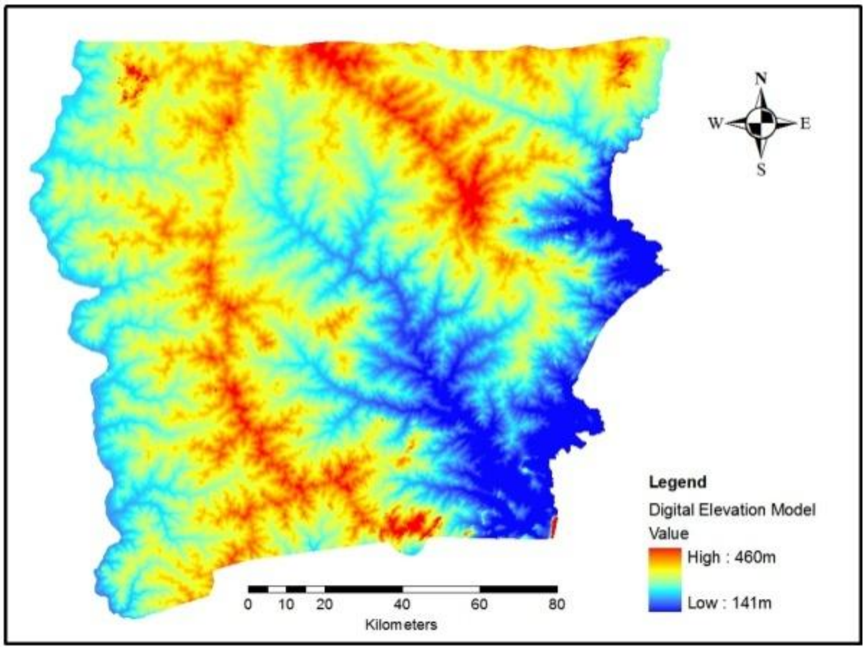

Figure 4. DEM of Study Area

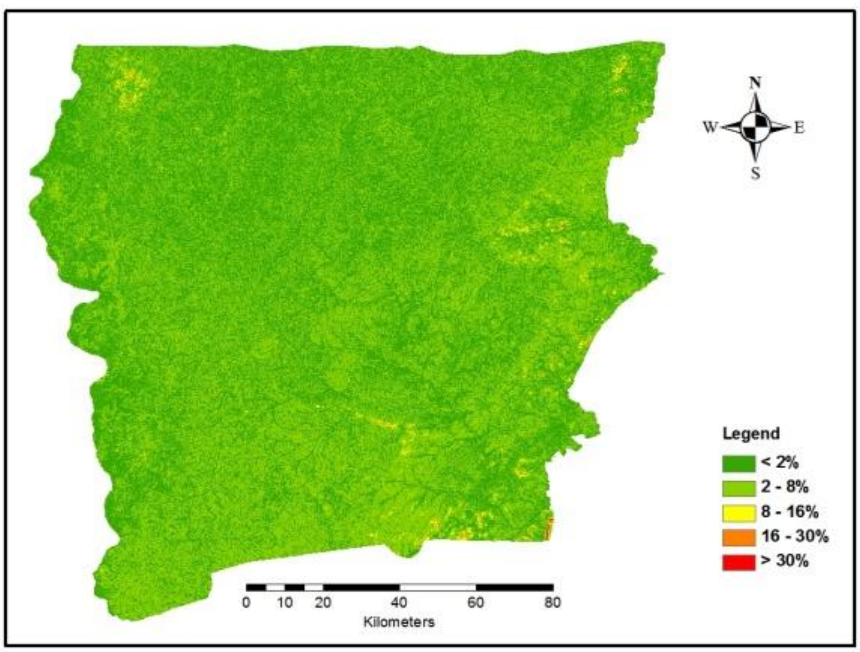

Figure 5. Reclassified Slope Map

Table 2. Suitability Level for Slope

Slope class	Slope (%)	Suitability Levels	
		Small Reservoir	Stone Bunds
Flat	<2	5	1
Undulating	2-8	4	3
Rolling	8-16	3	5
Hilly	16-30	2	5
Mountainous	>30	1	5

Adapted from FAO (2012)

3.3. Soil type

According to Girma (2009), soils with high infiltration rates are not suitable for most types of AWM interventions. It is thus deduced that soils with higher water holding capacity are more desirable when considering implementing and up-scaling of AWM interventions. For the purposes of this research, the FAO soil map of the world was used (Figure 6). The soil types identified were Luvisols, Vertisols, Acrisols, Nitosols and Lithosols. Depending on the soil texture proportions (Table 3) established by FAO (2012), the identified soil types were assigned suitability classes (Table 4).

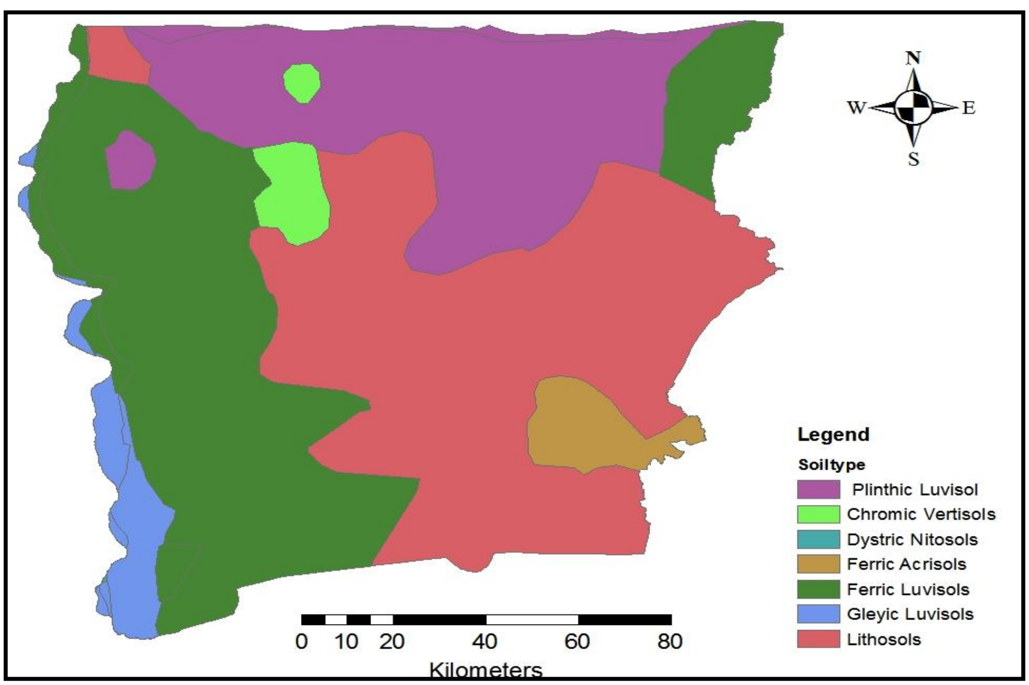

Figure 6. Soil Map of Study Area

Table 3. Soil Texture Proportions in Soil Types

Soil Type	Soil Layer	Sand Fraction (%)	Silt Fraction (%)	Clay Fraction (%)	Dominant soil texture
Acrisols	Topsoil	73	16	11	Sand
	Subsoil	61	11	28	
Luvisols	Topsoil	58	11	31	Sand, Clay
	Subsoil	51	7	42	
Vertisols	Topsoil	21	25	54	Clay
	Subsoil	20	24	56	
Lithosols	Topsoil	77	14	9	Sand
	Subsoil	67	16	17	
Nitosols	Topsoil	37	24	39	Clay, Sand
	Subsoil	30	31	39	

Modified from FAO (2012)

Table 4. Suitability Levels for Soil Type

Soil Type	Suitability Levels	
	Small Reservoir	Stone Bunds
Luvisols	4	5
Vertisols	5	3
Acrisols	2	2
Nitosols	4	4
Lithosols	2	2

Adapted from FAO (2012)

3.4. Rainfall-runoff Model

One of the most important parameters that need to be estimated when considering potential areas for AWM interventions is runoff. The model adopted in this study for runoff estimation is the Soil Conservation Service - Curve Number (SCS-CN) method. This model makes use of landcover and the hydrological soil groups in determining the weighted CN. The weighted CN is then used in equation 1 to determine the maximum retention (S). The runoff is finally estimated using rainfall (P) and the maximum retention (S) in equation 2.

To aid the use of the runoff values in the weighted overlay analysis, they are converted into a runoff map using surface analysis in ArcGis Interface.

$$S = \frac{25400}{CN} - 254 \qquad (1)$$

$$Q = \frac{(P - 0.2)^2}{P + 0.8S} \qquad (2)$$

where Q = Runoff depth (mm); P = Rainfall (mm); S = Maximum retention (mm); and CN = Curve Number.

In the process of calculating the runoff, the soil map is reclassified into four hydrological soil groups namely; A, B, C and D based on the infiltration and runoff generating potentials (Niehoff *et al.,* 2002).

3.5. Determination of Relative Importance Weight (RIW)

Another important factor that needs to be addressed before the weighted overlay analysis is the determination of the RIW of the various data input parameters. These parameters are weighted on a 9 point continuous scale (Figure 7) ranging from extremely less important to extremely more important (Saaty, 1980).

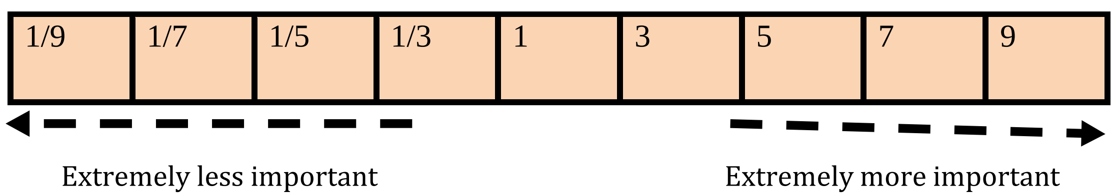

Figure 7. Continuous Rating Scale

Using the continuous scale, the thematic layers are weighted based on the comparative importance of each parameter with respect to the other parameters (Weerasinghe *et al.,* 2010). The weight index of comparative importance is estimated using the pair-wise comparison matrix (Tables 5 and 6) by determining the principal eigen vector using the process of averaging over normalized columns (Saaty, 1980). The formula is given as;

$$w_i = \frac{\sum_{i=1}^{I}\left(a_{ij}/\sum_{j=1}^{J} a_{ij}\right)}{j} \qquad (3)$$

where, W_i = weighted priority for component I; j = index number of columns; I = index number of rows; and a_{ij} = input parameter.

Table 5. Pairwise Comparison for Small Reservoirs

Parameter	Runoff	LULC	Slope	Soil type
Runoff	1	9	9	9
LULC	1/9	1	6	1/7
Slope	1/9	1/6	1	8
Soil Type	1/9	7	1/8	1

The different thematic layers (slope, soil type, runoff and landuse/cover) were compared using Saaty's (1980) Pairwise Comparison where he recommended that a scale of 1 to 9 be used to compare two components. A score of 1 represents indifference between the two components and 9 is the overwhelming dominance of the component under consideration (row component) over the comparison component (column component). If a component has some level of weaker impacts, the range of scores will be from 1 to 1/9 where 1 represents indifference and 1/9 being an overwhelming dominance by a column element over the row element. When scoring is conducted for a pair, a reciprocal value is automatically assigned to the reverse comparison within the matrix.

Table 6. Pairwise Comparison for Stone Bunds

Parameter	Runoff	LULC	Slope	Soil type
Runoff	1	8	8	8
LULC	1/8	1	1/7	1/5
Slope	1/8	7	1	6
Soil Type	1/8	5	1/6	1

Table 7. RIW of Input Parameters for AWM Interventions

Parameter	Relative Importance Weight (RIW)	
	Small Reservoir	Stone Bunds
Runoff	0.58	0.62
LULC	0.13	0.04
Slope	0.15	0.23
Soil Type	0.14	0.11

The RIW is an indication of the percentage influence of the various input parameters (i.e runoff, LULC, slope and soil type) under consideration for a particular type of intervention. The summation of the RIW for all input parameters considering a particular type of intervention should be equal to 1 when expressed as a fraction or 100 when expressed as a percentage. Shown in Table 7 is the RIW of input parameters for both small reservoirs and stone bunds.

3.6. Determination of Compound Suitability Index (CSI)

By combining the SLI and RIW, the potential site (CSI) for a particular intervention is identified by means of the weighted overlay analysis using ArcGIS 9.3. The higher the CSI, the more suitable an area would be for a particular intervention. The underlining equation used in the weighted overlay analysis is given by;

$$CSI = \sum (RIW \times SL) \quad (4)$$

where RIW = weight index for thematic layer for small reservoir/stone bund; and SL_{Sit} = suitability level of thematic layer for small reservoir/stone bund.

4. Results and discussions

4.1. Soil suitability mapping for small reservoirs

Figure 8 shows soil suitability for small reservoirs with the FAO soil map as basis as already discussed in the methods. From the analysis, as shown in Figure 8, vertisols with a corresponding percentage area of 2.03% is said to be optimally suitable for small reservoirs. Luvisols and nitosols with a cumulative percentage area of 58.60% were also found to be highly suitable for small reservoirs. Marginally suitable soil types were lithosols and acrisols with corresponding percentage areas of 36.53% and 2.85% respectively.

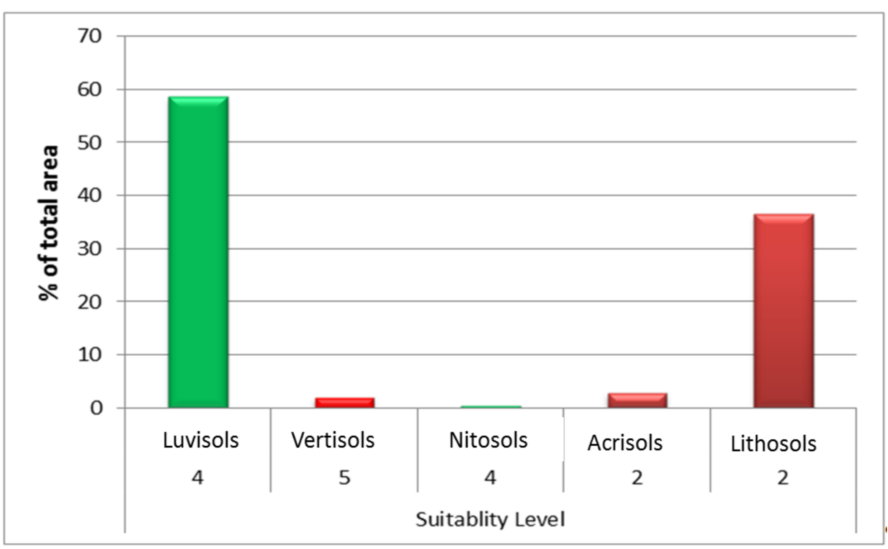

Figure 8. Percentage Soil Suitability for Small Reservoir

Small reservoirs are meant to hold water thus their underlying soil types should have a higher water holding capacity (FAO, 2012). This, thus makes vertisols which contains a greater proportion of clay (topsoil: 54% clay fraction and subsoil: 56% clay fraction) the optimally suitable soil type for this AWM intervention.

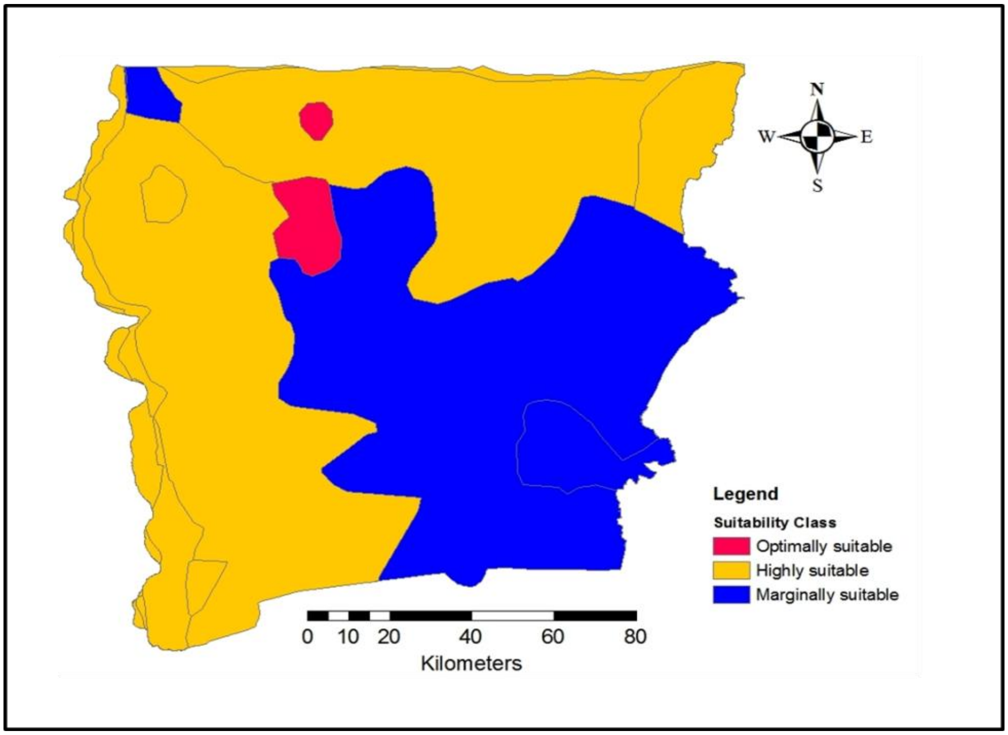

Figure 9. Soil Suitability Map for Small Reservoir

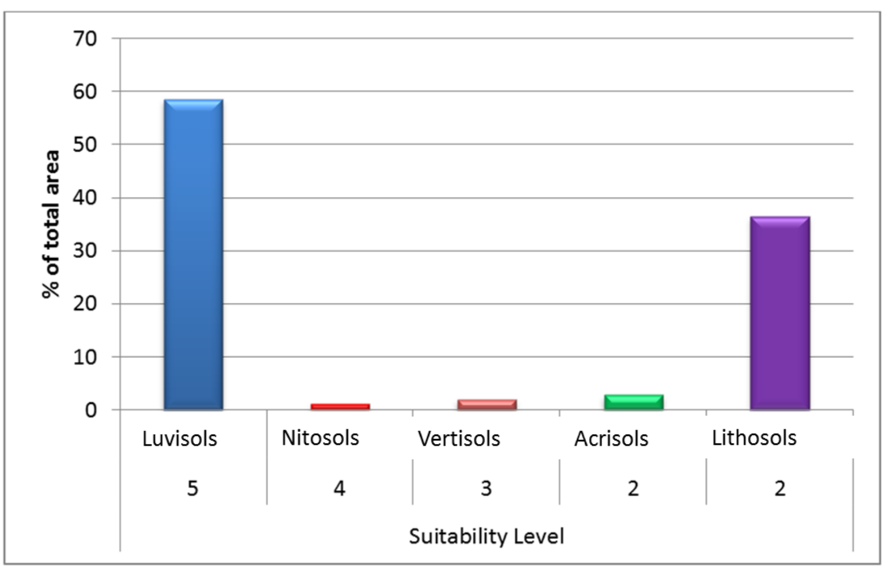

Figure 10. Percentage Soil Suitability for Stone Bunds

4.2. Soil suitability mapping for stone bunds

Suitability of soils for stone bunds in the order of optimal suitability to marginal suitability was luvisols, nitosols, vertisols, lithosols and acrisols (Fig. 11). From Fig. 10, the optimally suitable soil, luvisols covers a percentage area of 58.58%. The construction of stone bunds is to create small retention basin for runoff and sediment (Bosshart, 1997) and hence luvisols which has in greater proportion a mixture of sand and clay is a suitable soil type for this intervention. According to a study carried out by Nyssen *et al*. (2001), it was detected that stone bunds enhance the soil moisture especially in sandy and loamy soils and at a depth of 1.5m, soil moisture persist for at least two months after the end of the rainy season. Thus it is conclusive that stone bunds as an AWM intervention enhances soil moisture which consequently increases the availability of water for dry season farming.

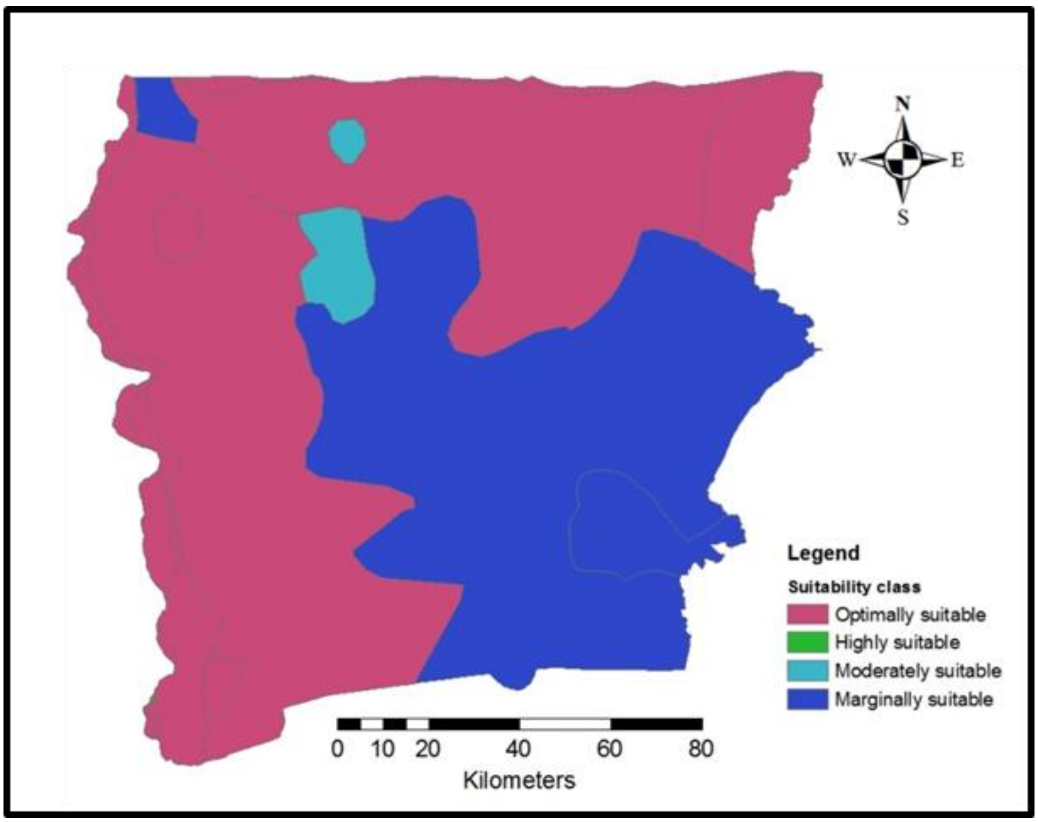

Figure 11. Soil Suitability Map for Stone Bunds

4.3. Landcover suitability mapping

Identified landcover types were deciduous woodland (28.99%), deciduous shrubland with sparse trees (59.29%) and cropland with open woody vegetation (11.72%). From the suitability analysis, the optimally suitable area for small reservoir was determined to be the cropland. Deciduous shrubland were determined to be highly suitable with deciduous woodland being marginally suitable. The areas corresponding to each landcover type, together with their suitability levels are as shown in Table 8.

Table 8. Percentage Area and Suitability Levels for Landcover Types

Landcover Types	Area (km^2)	Area (%)	Suitability Levels	
			Small Reservoir	Stone Bunds
Deciduous woodland	5496.41	28.99	Marginally suitable	Not Suitable
Deciduous shrubland	11242.62	59.29	Highly suitable	Moderately suitable
Cropland	2221.65	11.72	Optimally suitable	Optimally suitable

Since the interventions (small reservoirs and stone bunds) are geared towards improving cropping seasons and consequently crop yield, it thus becomes imperative to give higher considerations to cropland. From Table 8, cropland which is the optimal landcover type has a total area of 2221.65km^2. This forms only 11.72% of the total landcover types.

4.4. Potential areas for small reservoirs and stone bunds

Illustrated in Figure 12 and Figure 13 are the identified potential areas for small reservoirs and stone bunds respectively. From the analysis, the potential areas for small reservoirs had suitability levels of optimal, high and moderate whiles that for stone bunds were optimal, high, moderate and marginal. The percentage areas corresponding to optimal, high and moderate suitability levels for small reservoirs are 1.25%, 57.25% and 41.50% respectively (Table 9). On the other hand, the percentage areas with respect to the suitability levels of optimal, high, moderate and marginal for stone bunds are 3.14%, 85.40%, 11.04% and 0.42% respectively (Table 9). In both cases, the higher suitability level was predominant.

The optimal and high suitable sites for small reservoirs are located in areas with undulating slopes (0–8%). This is in agreement with the findings by Mbilinyi, *et al*. (2005), which assert that small reservoirs are constructed in areas where the slopes are such that water can easily enter and exit by gravity. The soil types located in areas with optimal and high suitability levels are luvisols which have relatively greater proportions of sand and clay. According to Ball (2001), soils with smaller particles like clay have a high water holding capacity and thus are deemed appropriate soil types for the construction of small reservoirs. The results also indicate that almost all the croplands located in the study area were located in areas described as highly suitable for small reservoirs. It could thus be deduced that farmers cultivate close to areas where small reservoirs exist in order to have access to water for their farming activities.

Considering stone bunds, optimal and high suitability areas were located where slopes were undulating (2-8%) and rolling (8-16%). These findings fall within the range 5-30% stipulated by Mbilinyi *et al*. (2007), to be suitable slopes for stone bunds. Stone bunds as an intervention are practiced on sloping areas where the soil type is unstable. The soil types identified in the optimal and high suitable areas for stone bunds are mainly lithosols, acrisols and luvisols. These soil types contain in higher proportion sandy loam which makes them suitable for the intervention. The landcover type that was found in the optimal suitable areas was cropland with deciduous shrubland and deciduous woodland which occupy the high suitable areas.

Table 9. Percentage Suitable Areas for Small Reservoirs and Stone Bunds

Suitable Area	Small Reservoirs		Stone Bunds	
	Counts	Area (%)	Counts	Area (%)
Optimal	194	1.25	489	3.14
High	8920	57.25	13306	85.40
Moderate	6467	41.50	1720	11.04
Marginal	0	0	66	0.42

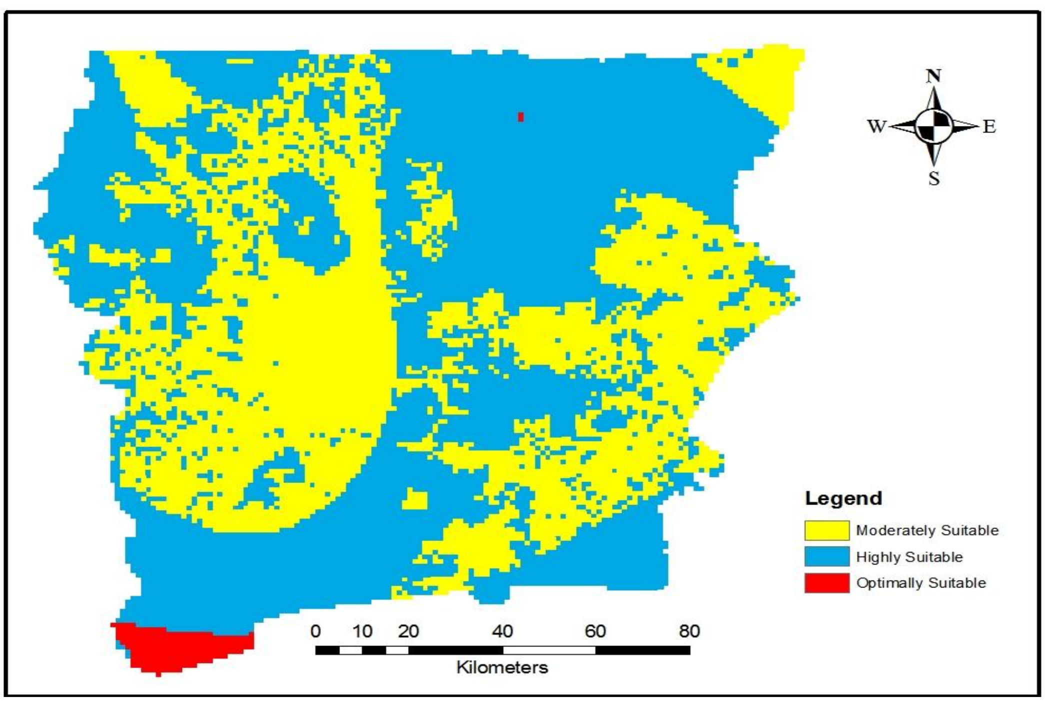

Figure 12. Map of Potential Areas for Small Reservoirs

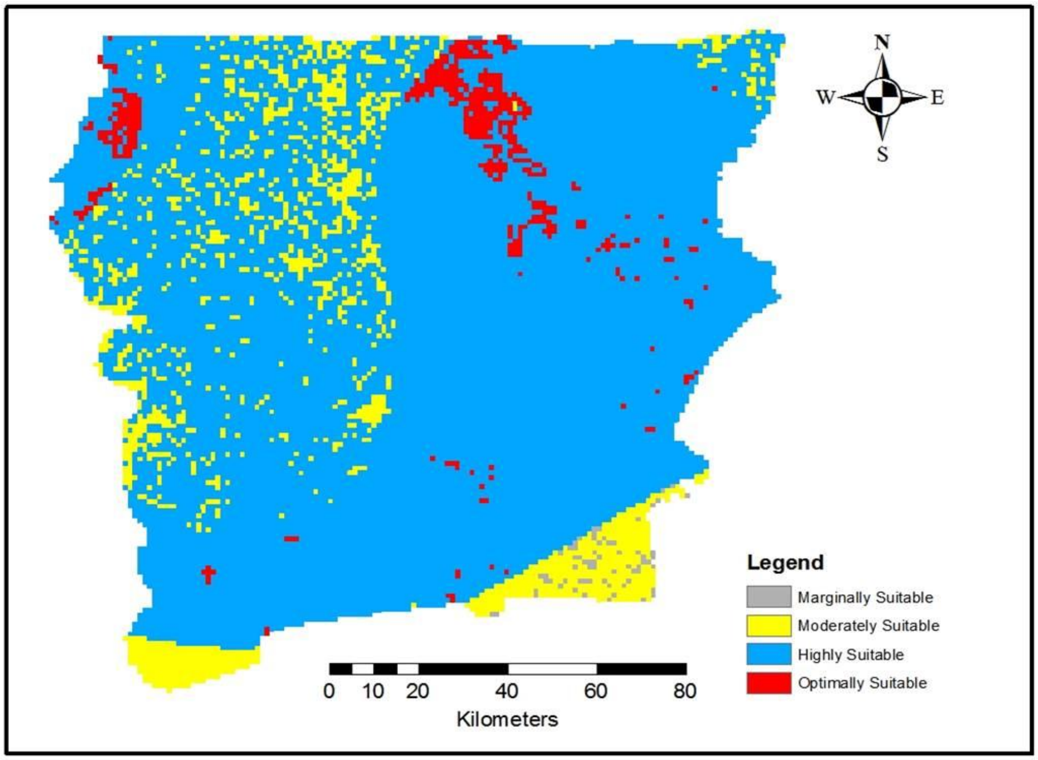

Figure 13. Map of Potential Areas for Stone Bunds

4.5. Validation of potential areas for small reservoirs

The validation of potential areas for small reservoirs was carried out by assessing the number of small reservoirs per each suitability area identified during the weighted overlay analysis. By superimposing the location of small reservoirs on the potential map generated for small reservoirs (Figure 14), it was found out that twenty-three (23) out of the 66 reservoirs in the region were located at moderately suitable areas. This represents 34.85% of the total number of reservoirs in the region. Forty-three reservoirs were found in the highly suitable areas representing 65.15% (Table 10). It is interesting to note that no reservoir was located in areas identified to be the optimal areas for small reservoirs. This could be attributed to the fact that reservoirs are sometimes sited based on other factors and/or reasons e.g. political or community demand and not necessarily on bio-physical factors.

Table 10. Number of Small Reservoirs per each Suitability Area

Area Suitability	No. of Small Reservoirs	% of Small Reservoirs
Moderate	23	34.85
High	43	65.15
Optimal	0	0

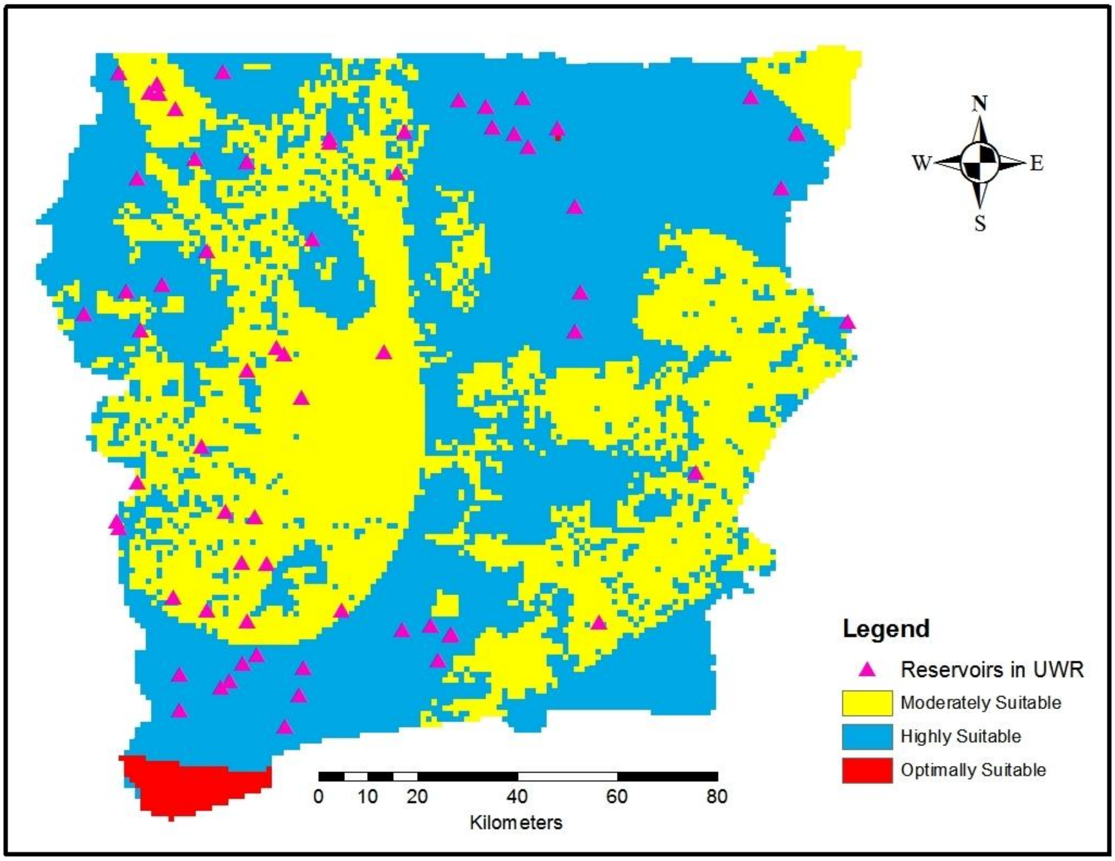

Figure 14. Validated Map for Small Reservoirs

5. Conclusions

In this study, potential areas for the implementation and scaling-up of AWM interventions have been mapped by combining four factors deemed to be essential to the successes of these interventions. The results indicate high potential areas of 57.25% and 85.45% for small reservoirs and stone bunds respectively. The study has further demonstrated the capable and flexible nature of using remote sensing and GIS techniques in the identification of possible areas where AWM interventions could be implemented. It is therefore recommended that this technique be used as a first point of call by decision and policy makers in the decision making process after which other factors could be incorporated to ensure effective utilization of available limited resources.

Acknowledgement

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