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Prioritization of Watersheds across Mali Using Remote Sensing Data and GIS Techniques for Agricultural Development Planning

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Abstract: Implementing agricultural water management programs over appropriate spatial extents can have positive effects on water access and erosion management. Lack of access to water for domestic and agricultural uses represents a major constraint on agricultural productivity and perpetuates poverty and hunger in sub-Saharan Africa (SSA). This lack of access is the result of erratic precipitation, poor water management, limited knowledge of hydrological systems, and inadequate investment in water infrastructure. Water management programs should be made by multi-disciplinary teams that consider the interrelationship between hydraulic and anthropogenic factors. This paper proposes a method to prioritize watersheds for water management and agricultural development across Mali (Western Africa) using remote sensing data and GIS tools. The method involves deriving a set of relevant thematic layers from satellite imagery. Satellite images from Landsat ETM+ were used to generate thematic layers such as land use/land cover. Slope and drainage density maps were derived from Shuttle RADAR Topography Mission (SRTM) Digital Elevation Model (DEM) at 90 m spatial resolution. Population grids were available from the Global rural-urban mapping project (GRUMP) database for the year 2000 and mean rainfall maps were extracted from Tropical rainfall measuring mission (TRMM) grids for each year between 1988 and 2014. Each thematic layer was divided into classes that were assigned a rank for agriculture and livelihoods development provided by experts in the relevant field (e.g., Soil scientist ranking the soil classes) and published literature on those themes. Zones of priority were delineated based on the combination of high scoring ranks from each thematic layer. Five categories of priority zones ranging from "very high" to "very low" were determined based on total score percentages. Field verification was then undertaken in selected categories to check the priority assigned to each class using a random sampling method. Watershed boundaries were prepared at 1000 ha scale and overlaid on the priority map to identify watersheds that were in a very high priority zone. The importance and efficiency of using remote sensing to prioritize watershed interventions across countries is critical due to the limited technical and financial resources available in sub-Saharan Africa (SSA).

Keywords: watersheds; prioritization; spatial data layers; scores; Mali; land use/land cover; suitability

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1. Introduction, Rationale and Background

The growth of the global population requires effective utilization of dwindling natural resources, especially for agricultural and livelihood needs. Natural resource development programs are generally applied on a watershed level [1]. Watersheds, catchments and sub-catchments are the fundamental units for the management of land and water resources [2]. In sub-Saharan Africa (SSA), despite existing inter-country agreements for sharing water of large river basins, small watershed programs for soil and water conservation and equitable domestic distribution were not a focus until recently. Poverty is the main focus of developmental programs in SSA that examine the reasons behind income disparities. Since two thirds of the population in SSA practice subsistence agriculture, sustaining a strong natural resource base will not only increase the productivity of land, it will also provide better livelihood opportunities and improve income. For development programs to be successfully implemented, watersheds need to be assessed as holistic units as a part of a larger river basin and containing a varied resource base. Identifying the natural resources within watersheds and appropriate streams that need immediate attention to sustain the population enables technological interventions such as improved crops, management practices, and coping mechanisms to issues like climate change to be implemented. Using interdisciplinary approaches to provide solutions to major problems, including management of water and other natural resources, is well recognized as being an effective way to address anthropogenic and natural factors in resource management. Although Mali has abundant water resources, they are poorly utilized due to lack of appropriate approaches and properly tested methods. The failure of watershed management programs, as concluded by the FAO workshop, is due to non-participatory nature and non-people centric goals [3].

Characterization of natural resources is possible with multi-disciplinary investigations that bring together a wide array of individuals and organizations with varied interests, technical expertise, and priorities. In this multi-disciplinary setting, prioritization of areas based on different bio-physical and social parameters such as population, soil conditions, rainfall, land scape and land use/land cover, are important. The land resource management concept identifies the inter relationship between social and biophysical factors [4–7].

Prioritizing the watersheds of appropriate scale has been mostly based on the morphometric characteristics and quantitative measurements. Attention has also been focused on the natural resources (such as soil and water) based conservation of watersheds. The human dimension and the interplay of these two was given a blind eye, despite its importance in successful implementation of natural resource plans. Many studies have shown that integration of multi-thematic maps, using remote sensing and GIS, is useful for identifying accurate groundwater potential zones for the exploration, development and management of groundwater resources [8–12]. A number of studies have been carried out to illustrate the capability of remote sensing and GIS technologies in natural resource studies and development planning [10,13–16]. The first pilot study in India using remote sensing and GIS was done in Karnataka state [17]. Javed and others [18] prioritized sub-watersheds in the Kanera watershed of Madhya Pradesh, India by using morphometric and land use analysis. Sadeghi [19] also did a similar analysis by giving more importance to land use in the watershed. Vemu and Pinnamanesni [20] used sediment yield estimation using USLE to prioritize the watersheds in the Indravathi basin of Andhra Pradesh in India. Li *et al.* [21] studied the impact of deforestation and overgrazing on erosion and water yield in the Niger and Lake Chad basins, and also identified a threshold effect of land cover type. In the Atankwidi sub-watershed of the Volta River basin in northern Ghana and southern Burkina Faso, a map of irrigated areas by shallow groundwater in was prepared using a similar approach [22]. In the present study, an attempt has been made to prioritize watersheds for proper natural resources management in Mali.

The main objective of this study was to prioritize watersheds across Mali for productivity enhancement and livelihood improvement. The specific objectives of the study using RS-GIS spatial analysis were to: (1) prepare critical spatial data layers needed for such analysis using remote sensing and GIS; (2) assign weights to classes in each spatial data layer based on expert knowledge; and (3) develop spatial model that will identify priority watersheds and provide answers to relevant questions for implementing development programs.

The study described is intended to contribute and build upon on the available databases to help identify watersheds with highest priority at a range of scales across Mali for agricultural and livelihood development. The method uses of standard hydrologic functions in GIS software to derive slope, drainage density and satellite image processing tools to derive land use map.

2. Study Area

This study focuses on Mali, which is the largest country among the Western African nations. It is bordered by seven nations: Algeria lies to the north and northeast, Niger to the east, Burkina Faso to the southeast, and Guinea to the southwest, with the Ivory Coast to the south along with Senegal and Mauritania to the west. In the southwest are low mountains deeply notched by valleys formed by the coursing of water. The climate ranges from subtropical in the south to arid in the north (Figure 1). In Mali, 22% of the country is semi-arid, 7.2% is dry sub-humid, and the remaining majority is arid (Table 1). Flooding of the Niger River occurs regularly in the rainy season (June to November) washing away soil nutrients and causing soil erosion. Four bioclimatic zones characterize the Malian landscape. The Sahara Zone is hyper-arid and desertic with water as the main constraint. Rainfall is low (0–250 mm) erratic and uncertain. The soils are sandy and skeletal based on the origin of material with poor water holding capacity. The Sahelian zone is characterized by long dry spells of 9–12 months. The Sudan zone is semi-arid to sub-humid with rainfall ranging from 550 mm to 1100 mm. The major crops in Mali are sorghum, pearl millet, cotton, maize and rice. The weather is usually sunny and dry and rains occur from July to November.

Mali is one of the nine countries drained by the River Niger, which runs its longest course in middle and southern areas. Being one of the two major water resources consumer countries of River Niger, Mali's 0.454 million square kilometers land is flooded providing irrigation to 0.122 million square kilometers of cotton and large tracts of rice and sugarcane. The drier reaches of the river are mostly rainfed and supports crops like corn, sorghum, millet and groundnut. These drier regions with diverse cropping patterns need the most attention for improving the livelihoods of the small holder farmers [23].

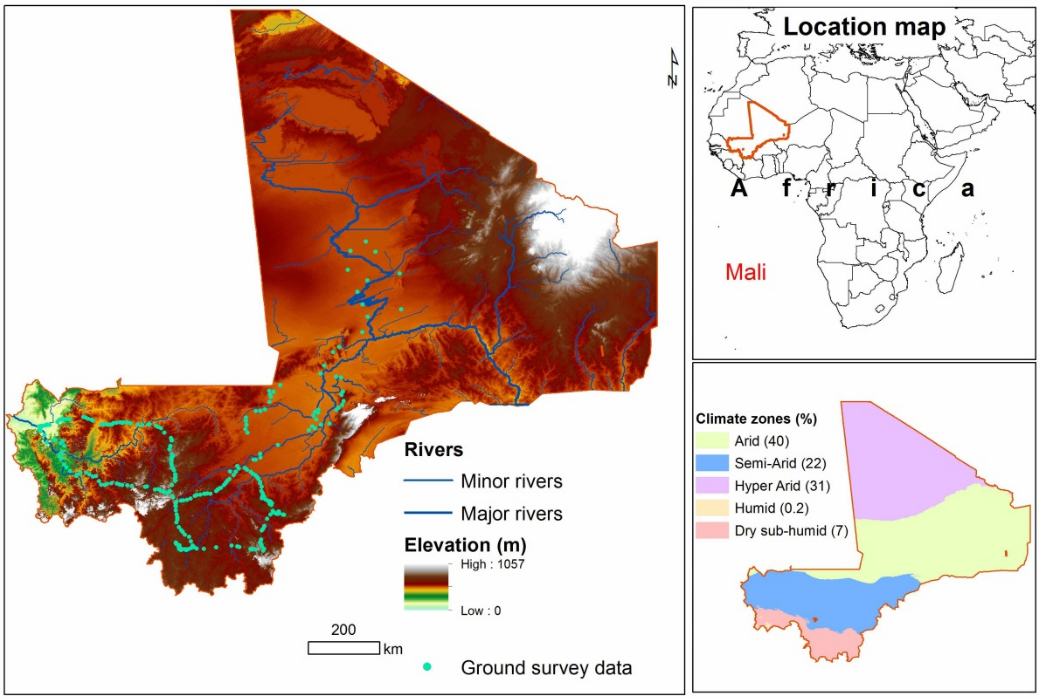

Figure 1. Location map of Mali with major rivers, Ground survey data and climate zones.

Table 1. Climate zones in Mali.

Climate Zone	Area (ha)	% of Total Area
Arid	50,407,233	40
Dry sub-humid	9,128,122	7
Humid	305,994	0.2
Hyper arid	39,352,637	31
Semi-Arid	27,293,862	22

3. Methods and Approaches

Determining priority watersheds (Figure 2) for agriculture and livelihoods development was achieved through weighted integration of multiple thematic layers. Relevant thematic layers dictating the agro-ecology and socio-economic conditions prevalent are prepared using different tools and techniques in remote sensing and GIS. In the absence of scientifically evaluated suitability criteria for priority setting, it was necessary to develop a method of spatial analysis based on the relevance and importance of information necessary for planning and development [12]. Expert knowledge of all the variables was obtained from relevant scientists to rank the values in each variable. Using a multi-criteria decision rule, priority classes were created.

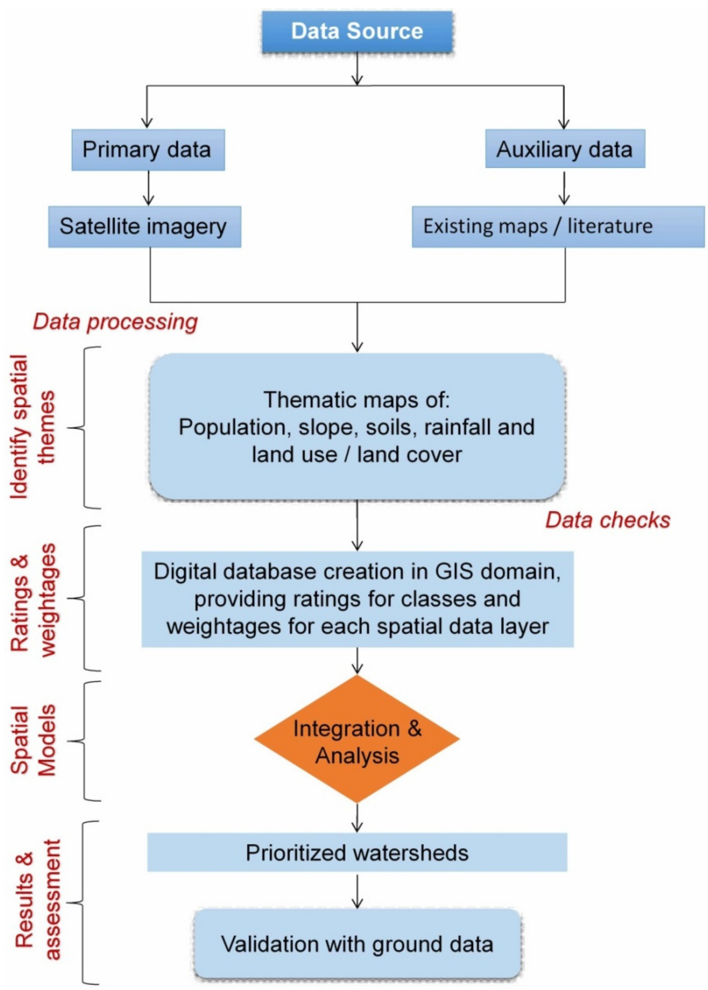

Figure 2. Overview of the methodology for watershed prioritization using integrated remote sensing and GIS techniques.

The thematic layers like Land use/Land Cover were derived from the satellite imagery (Landsat ETM+). Rainfall was derived from the Tropical Rainfall Measuring Mission (TRMM) sensors. Similarly other thematic layers were derived from available public domain sources. Each thematic layer was classified into appropriate number of classes with meaningful range (*i.e.*, 1 to 5). Weights or ranks were assigned for each class in a theme from a high numeric value to a lowest of 1 based on highest value of quantity or quality in the theme.

3.1. Criteria and Determining Factors

A set of relevant thematic layers such as soils, slope, land use/land cover, rainfall, population and their importance to development of natural resources were considered in the analysis. The relationships between the selected thematic layers based on the weights allocated determined homogeneous zones within Mali. The criteria to determine a prioritization category was a logical combination of weights of the thematic layers [24]. A high prioritization category was determined by criteria where each of the themes exhibits marginality, stress or poor resource base. Similar scoring of the thematic classes and combinations will determine other prioritization categories.

3.2. Input Data and Deriving Analysis Maps

3.2.1. Generation of Watersheds Using DEM

The most important input data in this study was the Space Shuttle Radar Topography Mission (SRTM) DEM of the world at 90 m horizontal resolution, which captured the varying topography of Mali (elevation range 15–1057 m). This is a gap filled DEM and made available through the Consortium for Spatial Information (CSI) web portal (http://srtm.csi.cgiar.org/). The SRTM DEM was used to delineate stream networks and slope. The drainage system was also delineated using SRTM DEM in sequence of steps as described below, in ArcGIS (ESRI 2009).

Filling sinks: When delineating stream networks form DEMs, it is necessary to fill sinks. A sink is a cell or set of spatially connected cells whose flow direction cannot be assigned to one of the eight valid values in a flow direction grid. This can occur when all neighboring cells are higher than the processing cell, or when two cells flow into each other creating a two-cell loop (ESRI 2009). Sinks in the DEM were filled up with the FILL function. It is an iterative process that goes to each cell and fills the sinks by comparing the value of neighboring cells until all the sinks are filled. Even though creating a depression less DEM was the goal, sinks were minimized to 0.1 million cells from 3.6 million.

Generation of flow direction: The direction of flow was determined by finding the direction of steepest descent from each cell. This was calculated as: maximize drop = (change in z-value)/(distance) $\times$ 100. The distance is determined between cell centers. Therefore, if the cell size is 1, the distance between two orthogonal cells is 1 and the distance between two diagonal cells is 1.414. If the descent to all adjacent cells is the same, the neighborhood is enlarged until a steepest descent is found (ESRI 2009). The function FLOWDIRECTION was used to calculate the direction of flow of each cell.

Generation of flow accumulation: Flow accumulation represents the accumulated flow in each grid cell. It was calculated by using flow direction and by counting the number of cells flowing to a particular cell. Thus, flow accumulation represents the number of upstream cells of any cell in an area. The FLOWACCUMULATION function was used to calculate this automatically while it takes the flow direction grid as input.

Generation of stream network: A set of thresholds of 10, 100 and 1000 pixels were used to generate stream network. All the cells in the flow accumulation grid that were above or equal to those threshold values were identified to generate raster linear networks. The output grids were then vectorized using the STREAMLINE function of ArcGIS, which takes raster linear networks and flow direction raster as input to produce linear vectors that also show the direction of flow (Figure 3). Once the streams were accurately derived, the watersheds (sub-basins) were delineated using available pour point.

Generation of watersheds: Pour points were generated to derive the fourth order stream network for the entire study area. Strahler's stream ordering method was used to categorize streams in to different orders based on the location of stream from stream head to tail of the watershed.

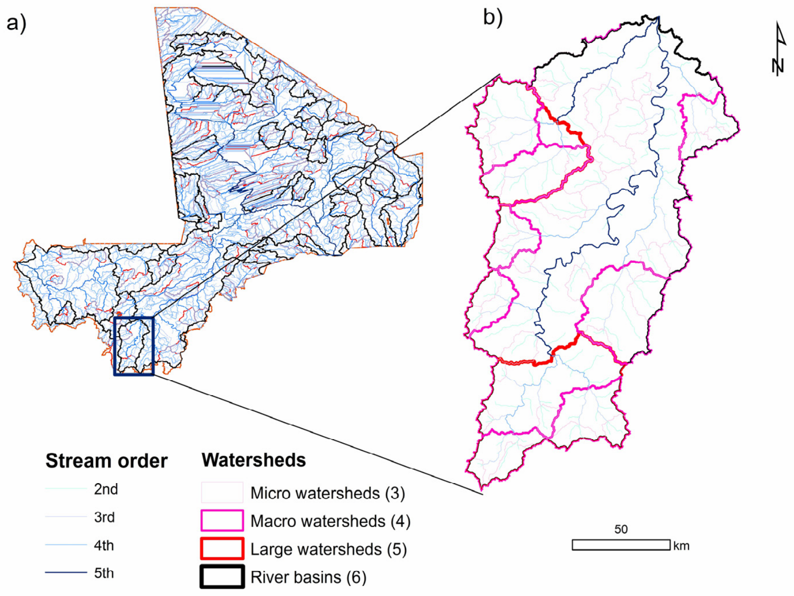

Figure 3. Fourth order watersheds in Mali derived using SRTM data: (**a**) fourth order watersheds for whole Mali; and (**b**) stream order network for selected area.

3.2.2. Population

The spatial distribution of population in Mali has a natural division between the Northern (Sahara) and Southern (sub-Sahara) parts. With a population of 16.4 million (July 2014 estimate) Mali has human development index ranking of 176 out of 187 countries. Half the population is under the age of 15. With a growth rate of 3%, the population of Mali has increased steadily from 6 million in 1976 to 14.5 million in 2012. The sex ratio is tilted towards females at 95 males/100 females. At current growth rates, the Malian population will reach about 30 million people in 20 years (5 times the population of 1976) with a density of 12.54 inhabitants per km^2 with implications such as pressure on natural resources, urbanization/migration, and rapid growth of social spending. The rural population is around 63.8% in 2013 according to World Bank estimates. Population was divided into 5 distinct classes, clearly indicating high rural population and a high density around the urban agglomerations (Figure 4a,b). These classes were assigned weights based on the scaling of total population. Higher population (in rural areas) was given a higher ranking relatively to prioritize the watersheds for a sustainable development and also stop migration to urban areas [25–27].

3.2.3. Land Use/Land Cover

Land use/land cover patterns were mapped and their areas were estimated (Figure 5, Table 2) using Landsat ETM+ 30 m spatial resolution satellite imagery. Landsat and MODIS MFDC were then classified using unsupervised ISOCLASS clustering K-means [28,29]. Land use classes were mapped based on ground data and land cover classes inferred from Google Earth high resolution imagery [30]. Irrigated land was assigned a score of five because it is mostly associated with flood plains and buried channels, which are very good recharge zones, as indicated by field derived information in the Upper East Region [31]. One of the dominant land use/land cover categories in the area is Class 4, Savannas: grasslands, shrub lands, and woodlands mixed with rainfed agriculture. In areas where there is high slope and thin soil cover, the groundwater prospects are considered to be poor and a score of one was assigned. Similarly, weights have been assigned subjectively to each of the categories of the land use/land cover pattern according to their influence on infiltration and runoff. The land use/land cover such as high gradient hill areas and settlements which have poor water holding capacity were given a score of one while savanna grass lands, irrigated areas and wetlands which are high water holding capacity were given a score of five (Table 2).

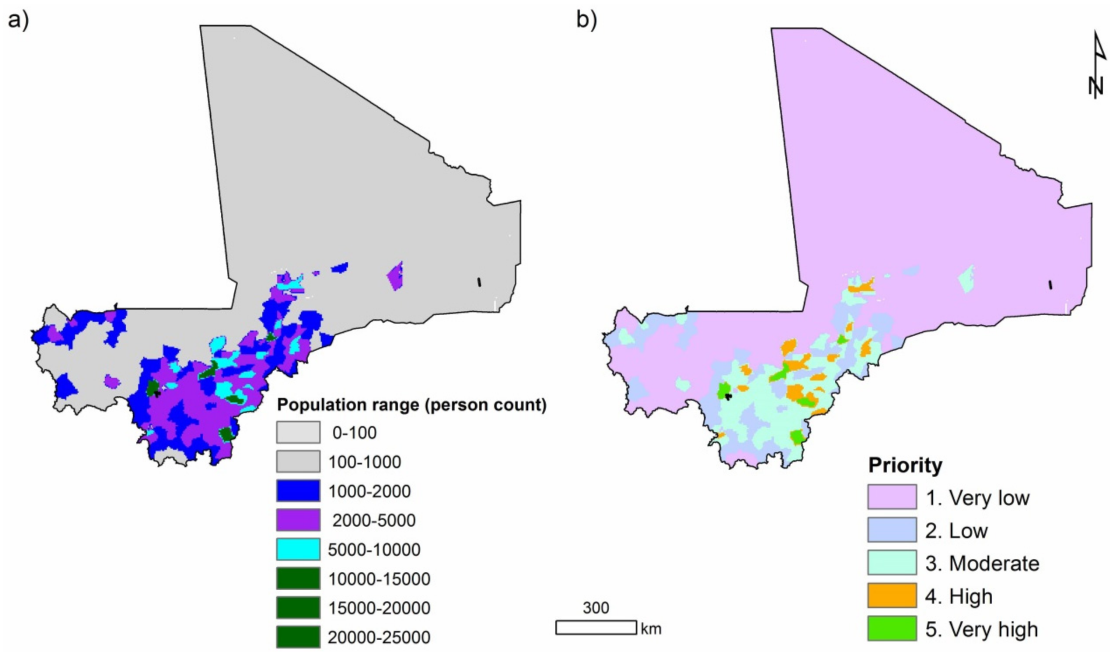

Figure 4. Spatial distribution of Population in Mali: (**a**) population count; and (**b**) priority category.

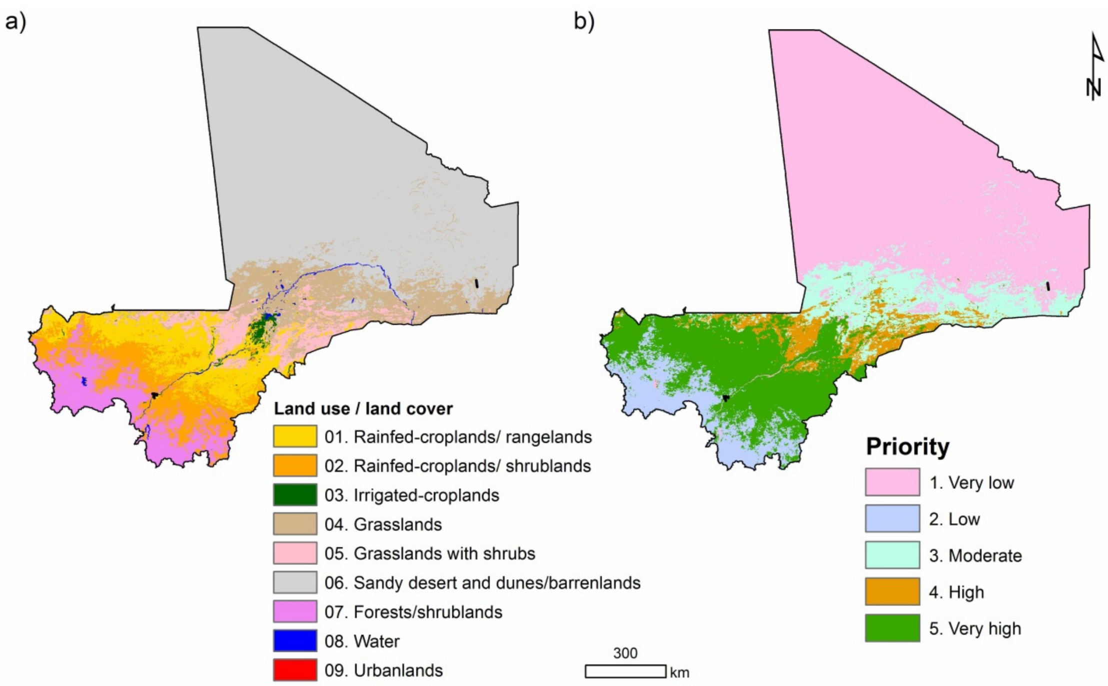

Figure 5. Land use/land cover classes in Mali, during 2000: (**a**) land use/land cover; and (**b**) priority category.

Table 2. Spatial distribution of the various parameters/themes, identified units within each theme and their associated areal extent within the study area.

Parameter/Theme	Identified Units/Score	Area (ha)	% of Total Area (%)	Priority Class	Scores Assigned	Weightage
Population	**Population Range (No. of people)**					3
1	0–1000	1,013,630	80	Very low	1	
2	1000–2000	111,395	9	Low	2	
3	2000–5000	109,756	9	Moderate	3	
4	5000–10,000	21,969	2	High	4	
5	10,000–15,000	6334	1	Very high	5	
6	150,00–20,000	288	0.02	Very high	5	
7	>20,000	1506	0.12	Very high	5	
Slope 90 m	**Slope distribution (%)**					3
1	<1 (level to nearly level)	156,338	12	Very high	5	
2	>1 and ⩽2 (gentle slope)	348,312	28	High	5	
3	>2 and ⩽3 (gentle slope)	376,179	30	Moderate	4	
4	>3 and ⩽4 (gentle slope)	258,617	20	Moderate	3	
5	>4 and ⩽5 (moderate slope)	62,198	5	Low	2	
6	>5 and ⩽6 (moderate slope)	22,319	2	Low	2	
7	>6 and ⩽7(moderate slope)	11,375	1	Very low	1	
8	>7 and ⩽8 (steep slope)	29,541	2	Very low	1	
Rainfall 0.5 degrees	**Annual rainfall (mm)**					5
1	0–100	133,902	11	Very low	1	
2	100–250	493,785	39	Very low	1	
3	250–500	249,031	20	Low	2	
4	500–750	187,961	15	Moderate	3	
5	750–1000	156,833	12	High	4	
6	>1000	43,367	3	Very high	5	
Land use 30 m	**Land use/land cover classes**					3.5
1	Rainfed-cropland/rangeland	124,603	10	Very high	5	
2	Rainfed-croplands/shrublands	108,438	9	Very high	5	
3	Irrigated-croplands	6541	1	Very high	5	
4	Grasslands	147,270	12	Moderate	3	
5	Grasslands with shrubs	64,843	5	High	4	
6	Sandy desert and dunes	706,371	56	Very low	1	
7	Forests/shrublands	101,191	8	Very low	1	
8	Water	5502	0	Low	2	
9	Urban lands	120	0	Very low	1	
Soils	**Soil type (Source: FAO)**					4
1	Cambic Arenosols	9633	1	Moderate	3	
2	Chromic Vertisols	10,985	1	Moderate	3	
3	Dystric Nitosols	8021	1	High	4	
4	Eutric Cambisols	2267	0	High	4	
5	Eutric Fluvisols	610	0	Very high	5	
6	Eutric Gleysols	124,973	10	Low	2	
7	Eutric Nitosols	12,859	1	High	4	
8	Ferric Acrisols	1177	0	High	4	
9	Ferric Luvisols	5797	0	Moderate	3	
10	FLUVISOLS	153,786	12	Very high	5	
11	Gleyic Luvisols	53,572	4	Moderate	3	
12	GLEYSOLS	4,751	0	Moderate	3	
13	Gypsic Yermosols	14,777	1	Low	2	
14	Haplic Yermosols	103,352	8	Low	2	
15	LITHOSOLS	153,088	12	Very low	1	
16	Luvic Arenosols	182,207	14	Moderate	3	
17	Pellic Vertisols	44	0	Moderate	3	
18	Plinthic Acrisols	1787	0	High	4	
19	Saltbeds	201,953	16	Very low	1	
20	Solodic Planosols	305	0	Moderate	3	
21	Takyric Solonchaks	174	0	Low	2	
22	Vertic Cambisols	4185	0	High	4	
23	Water bodies	1308	0	Very low	1	
24	YERMOSOLS	213,267	17	Moderate	3	

3.2.4. Slope

The SRTM DEM data was used to derive a slope map (in percent). Slope s one of the factors that directly influences the infiltration of rainfall in that steeper slopes generate large runoff during rainfall events, whereas gentle slopes allow sufficient time to infiltrate the surface [12]. Slope plays an important role in creating/arresting runoff and also ascertaining the land capabilities and suitability for different land uses and soil moisture. Slope was classified into thirteen categories [12] along with their areal extent (Figure 6, Table 2) and weights shown in Table 2. Weights were assigned according to the slope. A score of five was given to the plain region with lower slope because low runoff contributes to higher recharge.

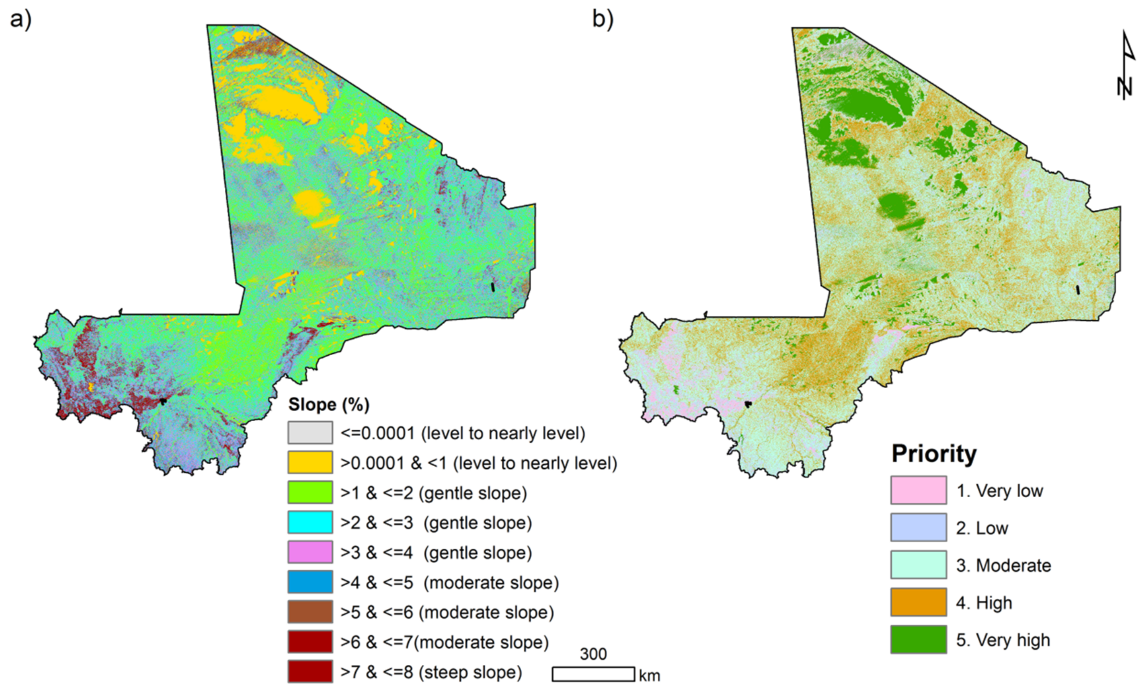

Figure 6. Slope map of Mali (extracted from SRTM DEM: http://srtm.sci.cgiar.org/): (**a**) slope class; and (**b**) priority category.

3.2.5. Soils

Soils are characterized by climate and physiography of the location and play an important role in prioritization. The water holding capacity of an area depends upon the soil types and their permeability. Soil types were classified into nineteen categories along with their aerial extent (Figure 7, Table 2) and weightages shown in Table 2. Field verification in the identified soil units were conducted and confirmed. Weights were assigned subjectively to each soil unit after taking into account the type of soil, specific yield and its water holding capacity. The soils that have poor water holding capacity have been given a weight of 5 and those with high water holding capacity were given a weight of 3.5 (Table 2).

3.2.6. Rainfall

Mean annual rainfall data for a 10-year period (1995–2005) was adopted from worldclim (http://www.worldclim.org/). Mali was divided into six rainfall zones (Figure 8) ranging from <100 mm to 1250 mm along with their areas shown (Table 2) and weightages shown (Table 3). An area receiving less than 100 mm of rainfall a year was given a score of one assuming a poor water availability zone, which are mainly located in northern Sahara region, while an area receiving greater than 1000 mm of rainfall was assigned a score of three assuming very good water availability in the southern region of Mali (Figure 8).

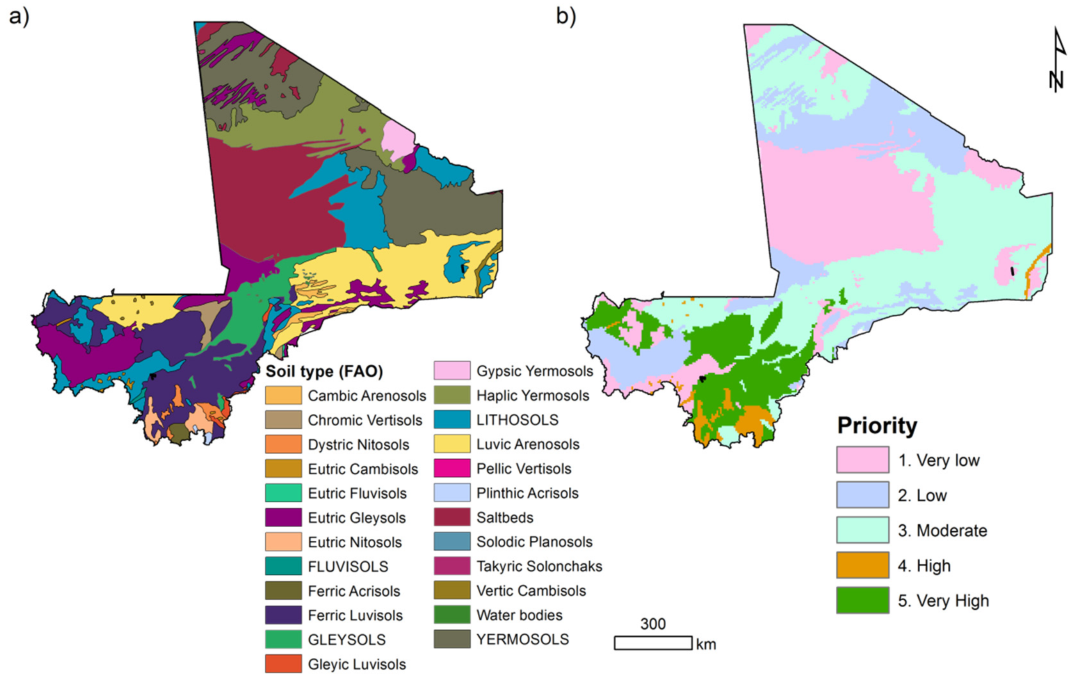

Figure 7. Soils of Mali (DSMW, FAO, 1995): (**a**) soil type; and (**b**) priority category.

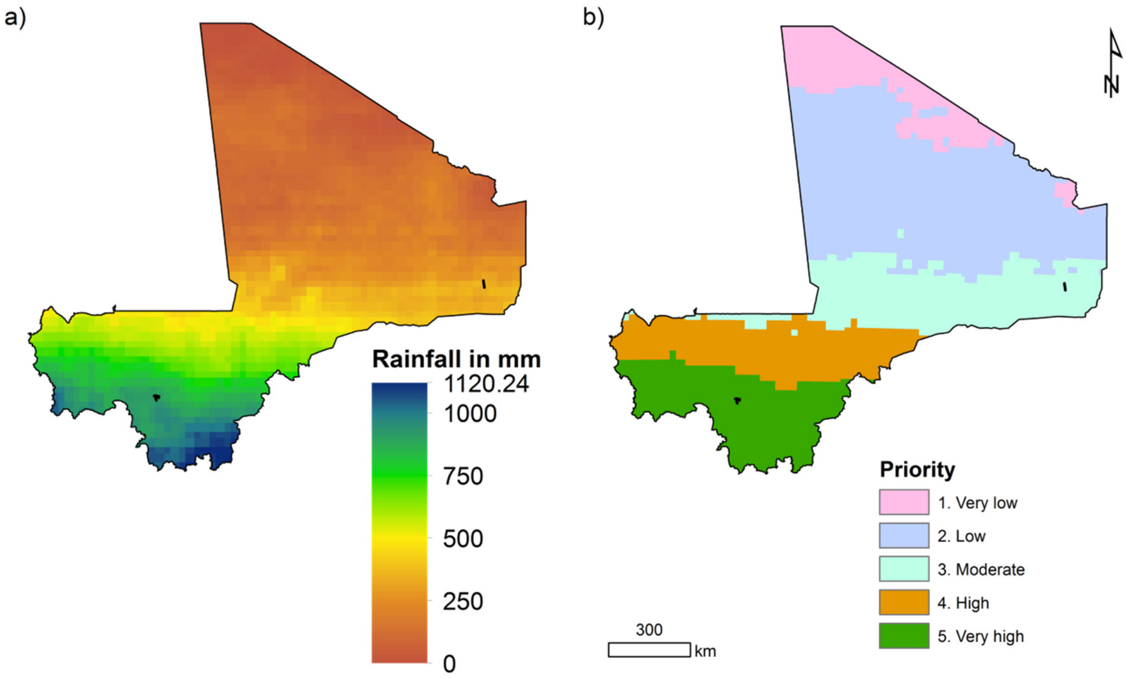

Figure 8. Mean Annual rainfall in Mali (taken from www.iwmidsp.org): (**a**) normal annual rainfall; and (**b**) priority category.

Table 3. Prioritization of watersheds across Mali with % extent.

Groundwater Potential Class	Total Score (%)	Area (ha)	% in Total Area
1st priority (very high)	100–85	4,985,646	4
2nd priority (high)	85–70	29,105,968	23
3rd Priority (medium)	70–60	14,817,795	12
4th priority (low)	60–45	51,617,548	41
5th priority (very low)	⩽45	25,960,891	21
Total areas		126,487,848	100

3.3. Determining Thematic Layer Weights

Suitable weights were assigned to the five themes and their individual classes after understanding their importance in setting priorities to watersheds in Mali. The weights of the individual themes were assigned based on expert knowledge and published literature [5,10,12,32,33] in Table 2. The assigning of weights to each of the thematic layers was purely based on the merits of the layer in arriving at a priority rank to a watershed. The importance of each theme was determined based on previous literature [12]. The percent importance assigned to each themes are as follows: population—17%; slope—21%; rainfall—26%; land use/land cover—18%; and soils—18%. Therefore, the higher the weight, the more influence a particular factor will have in the watershed prioritization model. In this study, we defined the maximum weight as five and the minimum weight as one.

3.4. Integration of Thematic Layers and Spatial Model

The first step in the spatial model development was to devise a scheme of classification for each thematic data layer and the ranks assigned to each class. (Table 2). ERDAS spatial modeler was used to derive and apply this model. All reclassified themes were integrated in weighted overlay analysis using Equation (1).

$$\boldsymbol{WSP_P} = \Sigma\ \boldsymbol{T_{GW}} \times \boldsymbol{F_W} \quad (1)$$

where $\boldsymbol{WSP_P}$ is the Watershed priority score of pixel score in model output; $\boldsymbol{T_{WS}}$ is the selected watershed priority theme; and $\boldsymbol{F_W}$ is the Weightage factor of theme.

4. Results and Discussion

4.1. Prioritization of Watersheds

After rescaling of the thematic maps to five classes using the scores, the integration process resulted in a prioritized area map with the following categorization. On the basis of the $\boldsymbol{WSP_P}$ value, watershed priorities were classified as: (i) very high priority; (ii) high priority; (iii) medium priority; (iv) low priority; and (v) very low priority across the study area (Figure 9; Table 3). Highly scored thematic classes and their combination were categorized as a high priority zone and *vice versa*. It was determined that very high priority should be given to watersheds in central and southern Segou, the northern and eastern part of Sikasso, and the southern and southeastern part of Koulikourou regions. With an area of 4.99 Mha, in the very high priority zone in Segou (1.86 Mha), Sikasso (1.83 Mha) and Koulikoro (1.11 Mha) regions, there is good potential for developing the rainfed cropland/shrub lands where water scarcity is a major constraint. High priority should be given to watersheds in southern and western parts of Sikasso (4.39 Mha), northern parts of Kayes (4.94 Mha), Koulikoro (6.22 Mha), Segou (3.82 Mha), southern Timbouktou (2.52 Mha) and most of Mopti (5.60 Mha) regions covering 29.1 Mha. Very low priority was given to the southern part of Kayes region. A moderate priority zone was delineated across the central region of Mali covering the southern parts of the Timbouctou and Gao regions. The central and northern parts of Timbouctou and Gao regions were categorized as low and very low due to extreme weather and low natural resource base. The total area under first priority was 4.9 Mha, which accounts for 4% of the total geographical area. The second priority zone is 29 Mha

(23%); third priority zone was 14.8 Mha (12%); fourth priority zone was 51.6 Mha (41%); and very low priority zone was 25.9 Mha (21%) (Figure 9 and Table 4).

The spatial resolution of each thematic layer determined the amount information in that layer *i.e.*, the higher the resolution, the more classes were resolved to assign appropriate weights to each class. Finer classes in each theme will increase the accuracy of prioritization, which will be useful for targeting interventions in smaller watersheds. Coarse resolution thematic layers generalize classes and less information over certain diverse landscapes may cause undue weightage to a particular class resulting in inappropriate priority rating. Hence, it was necessary to decide on the resolution of the thematic layers based on the extent of area to be prioritized.

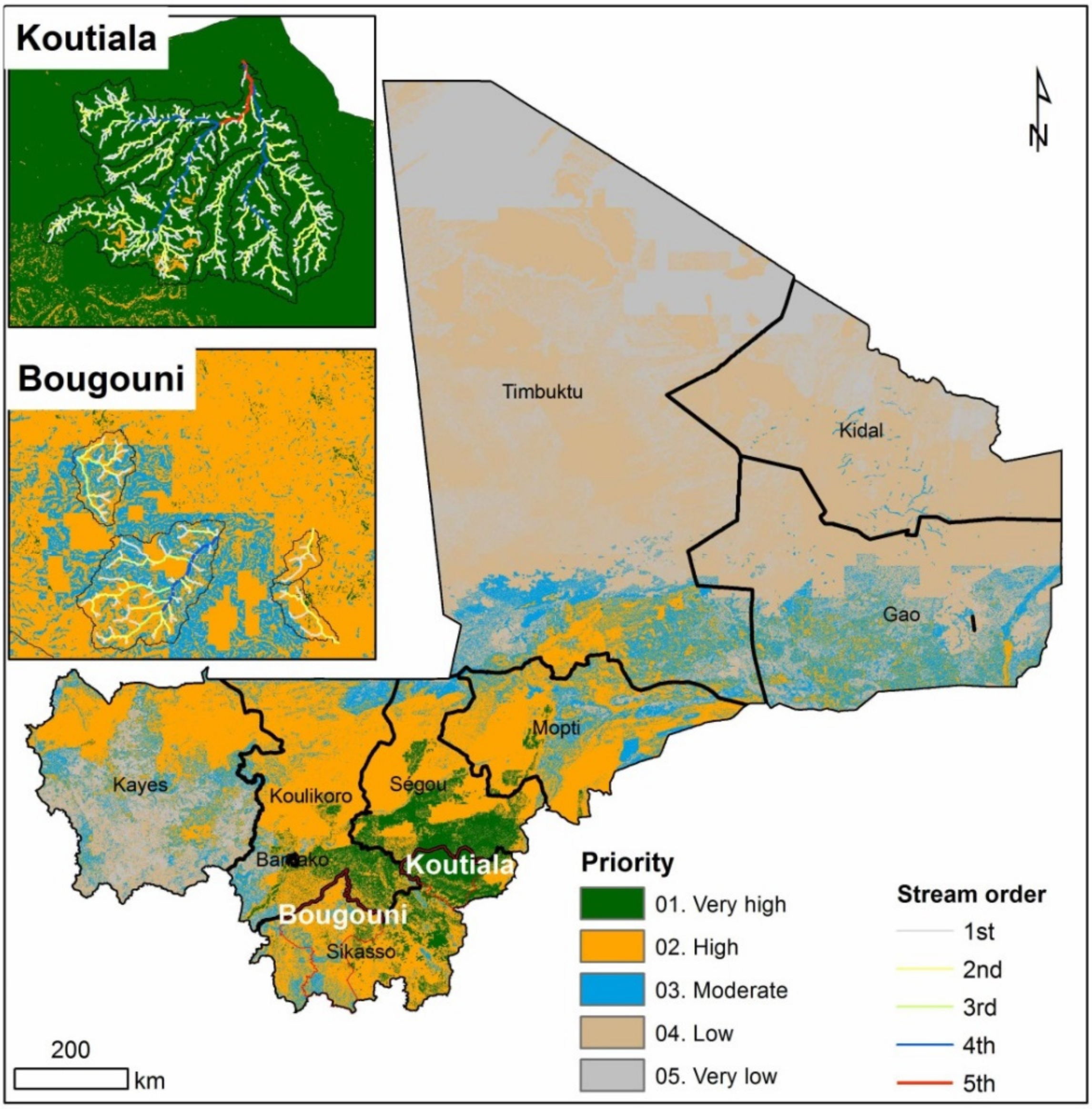

Figure 9. Priority zones for watershed based development across Mali. Test sites selected before this study (inset).

Table 4. Potential areas for watershed interventions.

Region	Potential Area (Mha)				
	1st Priority (Very High)	2nd Priority (High)	3rd Priority (Medium)	4th Priority (Low)	5th Priority (Very Low)
Bamako	0.01	0.02	0.00	-	-
Gao	-	1.59	4.31	11.04	1.19
Kayes	0.01	4.94	2.41	4.01	0.84
Kidal	-	0.00	0.15	10.79	3.99
Koulikoro	1.11	6.22	1.18	0.56	0.02
Mopti	0.17	5.60	1.88	0.42	0.01
Sikasso	1.83	4.39	0.79	0.12	0.02
Segou	1.86	3.82	0.39	0.09	0.00
Timbuktu	0.00	2.52	3.70	24.60	19.86
Total	4.99	29.10	14.81	51.61	25.92

4.2. Development of Spatial Model

Two models were developed: one of which was developed taking the Equal weights and variable scores [24].

Pixel score in model output = weightage of layer 1 × weightages of classes within layer 1 + weightage of layer 2 × weightages of classes within layer 2 + . . . + weightage of layer n × weightages of classes within layer n.

High priority watersheds were selected based on this method in Koutiala and Bougouni districts in southern region of Mali. Four sub-watersheds were selected in different parts of Koutiala and Bougouni districts each to introduce best management practices based interventions for sustainable agriculture. Coincidentally, it was found that these watersheds were part of the Africa RISING project where several CGIAR centers and local partners are implementing development interventions for improving water availability and increasing productivity. One of the important inputs in this method was the accurate mapping of LULC using remote sensing imagery. This served the dual purpose of mapping as well as conducting farmer interviews to understand constraints, which in turn will help us in assigning appropriate weights for prioritization.

4.3. Validation with Ground Survey Data

Ground survey data was collected for 495 locations during 3–13 August 2015. Local agriculture experts accompanied the lead author during the field visit and farmer interviews and local experts provided detailed information at each location. Each location was selected based on representativeness of land use/land cover including major crop types. The 180 locations that had detailed ground information were collected, which was used for class identification and remaining 315 locations were used for validation of land use/land cover map and prioritization map.

The nine class land use/land cover map produced from satellite imagery was validated with 315 ground data points and an error matrix was produced (Table 5). For nine LULC classes 266 out of 315 ground points matched with the derived class, resulting in an accuracy of 84.44% and Kappa value of 0.796.

The five-class prioritization map produced was validated with 315 ground data points and an error matrix was produced (Table 6). For all five classes, 253 out of 315 ground points matched with the derived priority class, resulting in an accuracy of 80.32% and Kappa value of 0.689.

Table 5. Accuracy assessment of land use/land cover map using field-plot data using error matrix method.

Classified Data		Reference Data (Classes)										Accuracy	
		01	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**Row Totals**	**Producers Accuracy**	**Users Accuracy**
Landsat derived classification	01. Rainfed-croplands/Mix with shrubs	96	0	0	2	9	0	1	0	0	108	93%	89%
	02. Rainfed-croplands/Plantation	1	82	3	4	5	0	13	0	1	109	96%	75%
	03. Irrigated-croplands	0	0	16	0	0	0	0	0	0	16	84%	100%
	04. Grasslands	0	0	0	14	0	1	0	0	0	15	70%	93%
	05. Grasslands with shrubs	0	0	0	0	14	0	0	0	0	14	50%	100%
	06. Sandy desert and dunes	0	0	0	0	0	9	0	0	0	9	90%	100%
	07. Forests/shrublands	6	3	0	0	0	0	34	0	0	43	71%	79%
	08. Water	0	0	0	0	0	0	0	0	0	0	-	-
	09. Urbanlands	0	0	0	0	0	0	0	0	1	1	50%	100%
Column Total		103	85	19	20	28	10	48	0	2	315		

Note: Overall Classification Accuracy = 84.44%; Overall Kappa Statistics = 0.796.

Table 6. Accuracy assessment of prioritization map using field-plot data using error matrix method.

Classified Data		Reference Data (Priority Classes)					Row Totals	Producers Accuracy	Users Accuracy
		01. Very High	**02. High**	**03. Moderate**	**04. Low**	**05. Very Low**			
Prioritization map	01. Very high	80	7	6	0	0	93	90%	86%
	02. High	8	139	12	6	0	165	87%	84%
	03. Moderate	0	11	19	2	0	32	50%	59%
	04. Low	1	3	1	13	5	23	62%	57%
	05. Very low	0	0	0	0	2	2	29%	100%
Column Total		89	160	38	21	7	315		

Note: Overall Classification Accuracy = 80.32%; Overall Kappa Statistics = 0.6892.

5. Conclusions

This research illustrates the development of a spatial modeling approach for prioritization of watersheds across Mali for agricultural and livelihood development. The process involved: (a) identifying and developing harmonized spatial database; (b) allocating weights to spatial data layers and classes within each data layers based on expert knowledge and previous literature; and (c) developing spatial relationships between layers by ranking the combination of weights and established priority zones. The model provided the various levels of development priority zones, percentage areas, and precise location of these areas. This method prioritizes watersheds in Mali for agricultural development but does not include action plan for each watershed. However, some watersheds that were selected under a different project for implementing agricultural development interventions are found to coincide with the priority category derived using the proposed method indicating the usefulness of this type of prioritization.

The study highlights priority zones across Mali and identified watersheds that are predominantly agricultural and need appropriate intervention to improve productivity. The outcome of this methodology paper also highlights the utility of spatial modeling, and the importance of spatial databases at different scales and resolutions for mapping prioritization of watersheds for development planning. When the sub-basins and small watersheds are selected for implementation of development activities, it is necessary to use higher spatial resolution thematic layers and ancillary data.

The accuracies of land use/land cover map and prioritization map were assessed based on intensive ground survey data. The overall accuracy of five prioritization classes was 80%. However, high and very high priority class accuracy exceeded 85% and also previously selected Africa RISING research study sites coincide with these classes. Mapping prioritization of watersheds is the first step in implementation of agricultural interventions for sustainable development and livelihoods. This approach was appropriate for planning and disseminating technologies. We suggest that this methodology can be improved and adopted for prioritizing watersheds in other countries in sub-Saharan Africa where productivity of land can be increased using improved technologies. This research makes a broader contribution to methods and products of the group on Earth observation for sustainable agriculture development and supporting future food security.

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