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GIS Based Physical Land Suitability Evaluation for Crop Production in Eastern Ethiopia: A Case Study in Jello Watershed

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Abstract

This study was aimed at identifying the current physical land suitability for maize, wheat and sorghum in Jello watershed under Chiro woreda in accordance to the FAO (1976) framework. The suitability mapping carried out with the help of GIS was compare with the LU being practiced. Relevant land quality (LQ) and land characteristics (LCs) data on climate, topography and soil following medium intensity survey technique were collected and the analysis was held after converting the data into a usable format for the LE process. Consequently through the querying analysis, the suitability rating process was run for individual LCs and based on the maximum limitation method, the overall suitability was assigned for specific land mapping units (LMUs) and displayed as suitability map with the integration of GIS. Results showed that out of the 1650ha, wheat production was moderately suitable (S2) on 6%; marginally suitable (S3) on 33% and not appropriate (N) on 61% of the land. 52% and 48% of the area was marginally suitable (S3) and unsuitable (N) for maize cultivation respectively. 33% of the area was marginally suitable (S3) and the rest (67%) was not suitable (N) for sorghum. Overall, presently none of the thirty three LMU fell under highly suitable (S1) class and based on the individual LCs, fertility status (exceedingly available P not assigned as S1) was found to be the most severe limiting factor. The comparison made between the existing land use being practiced and the findings from this study showed, 800ha (48%) and 1100ha (67%) area of land was mismatched (currently not suitable) for maize and sorghum cultivation respectively. Based on the analysis, wheat cultivation is relatively better (moderately suited) than the land use being practiced (maize and sorghum) on the bases of the present situation for 100ha (LMU23 and 30).

Keywords: Crop production; Ethiopia; GIS; Land evaluation; Limitation method

Introduction

Land needs careful and appropriate use that is vital to achieve optimum productivity and to ensure environmental sustainability for future generation. This requires an effective and operative management of land information on which such decisions should be based because land is one of the non-renewable natural resource. Decision on appropriate use includes the past and present human activities [1] and the status of physical and chemical properties of the land. Land evaluation (LE) is concerned with the assessment and valuation of land when used for specified purposes. It involves the execution and interpretation of basic surveys of data on climate, soils, vegetation and other aspects of land in terms of the requirements of alternative forms of land use. To be of value in planning, the range of land uses considered has to be limited to those which are relevant within the physical, economic and social context of the area considered [2].

According to [3] the utmost pertinent solutions for the utilization of land resources in sustainable way is land-use plan by proposing alternative measures and combine the different land characteristics to solve land misuse problems. Obviously to collect, store, incorporate and analysis the different land attributes that differ spatially, Geographic Information System (GIS) could be applied [4].

Ethiopia's social and economic development is highly dependent on agriculture. Leading industry and future overall country development is also expected to be driven by the progress in the agricultural sector [5]. Even if Ethiopia is endowed with rich biodiversity, throughout the country the speedy expansion of cultivation, settlements and other human activities in combination with unsustainable natural resource management even in unsuitable land has increasingly grown.

These expansions clearly exert pressure on the resource of land especially shifting of marginal and forestland in to cultivation purpose is a common practice. This is a great threat for resources as well on the resultant socio-economy, and environmental components since agriculture normally involves clearance of any natural vegetation present [2]. Due to improper land use, over exploitation and mismanagement of natural resources coupled with socio-economic factors, the problem of land degradation is on the rise and has become an issue of concern [6].

To combat land degradation, harmonizing the often-conflicting objectives of intensified human needs and socio-economic development, while maintaining and enhancing the ecology life support functions of land resources is a must. Land suitability evaluation is very important to provide information on the constraints and opportunities for the use of the land and therefore guides decisions on optimal utilizations of the resources [7]. This enables to guarantee the long-term productive potential of these resources all together by a compound effort which progressively brings the resource degradation under control [8].

At Jello watershed et al. [9] reported that an increase in cultivated

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and settlement lands by 55% and 107% respectively with a decline in forest lands by 80% occurred over the 30-year period since 1966. Hence, human activities are expanded onto marginal areas because the local people are entirely dependent on natural resources for their livelihood along with other physical, socio-economic and political factors. These intense changes in land use/land cover may result a significant resource imbalance due to the incompatibility of the land with land use, over exploitation of the resource and mismanagement in terms of its capability and suitability.

Though crop production is dominant in the area, the land is not evaluated/assessed and used according to its natural capability and suitability for wheat, maize and sorghum. Such types of land use practice which may seem to be highly profitable in the short run will likely to take the lion sharing to cause soil erosion and resource degradation. Such trends in agricultural production and natural resource status of the land parcel require crucial efforts for the reason that proper use of land depends on its suitability for a specific purpose that integrates different measures in sustainable way [2]. Therefore, the principal goal of this study was to perform the actual qualitative land suitability evaluation and carry out suitability mapping for the existing land use types (wheat, maize and sorghum) with an understanding of the limiting factors by integrating different information using GIS tools. Comparison between the present land use being practiced and the findings from this study was also accomplished.

Materials and Methods

Study area

The study area is situated in Najabas kebele of Chiro Woreda of West Hararghe Zone in the Oromiya region (Figure 1) around 326 km east of Addis Ababa. Its altitude extends between 1780-2660 m.a.s.l and the average annual rainfall is 751.3 mm [10]. During the rainy months, farmers plant sorghum, maize, wheat, inter-cropping with chat and in some parts of the area vegetables like onion, tomato and cabbage and banana as fruit tree. The area of interest covers a total of 1650 ha and agriculture is the major livelihood of the people.

Data collection methods

Secondary data; climatic data records (Figure 2), topographic map and the LU practices were obtained from the Department of Land Resource and Environmental Protection of the woreda.

A medium intensity soil survey (1:50,000) was used, soil sampling density of one observation for 50 ha [11]. Consequently, a total of thirty three land mapping units (LMU) were prepared over the entire 1650 ha area (Figure 3a) and one representative profile pit for each LMU was also opened (Figure 3b) and geographically referenced by using GPS. A soil sampling technique in a zigzag pattern was implemented as recommended by [12], to make it more representative; twenty sub-samples of the same amount were collected from each LMU at two different fixed rooting depths (0-30 cm and 30-60 cm) separately and later, the sub-samples from similar depth were mixed carefully to made a composite sample. As a result, a total of sixty six composite soil samples over the entire area were prepared, and analyzed. Rooting depth was measured using a measuring stick; surface stoniness was estimated by selecting plots randomly to make it representative. Measurement was replicated five times and the average value was recorded in terms of areal percentage for each LMU [13]. Soil drainage class was assessed using soil profile color in combination with depth of mottling occurrence [14,15]. Flooding or inundation condition was characterized by flooding duration based on the information obtained from local people [15]. The average slope gradient was measured using clinometer aimed in the direction of the steepest slope [16].

Data analysis methods

Soil analysis: Bouyoucos hydrometer method was used for textural analysis and according to USDA system textural triangle was used for grouping of soil textural classes [17]. Soil pH was determined using a pH-meter with soil to water suspension ratio of 1:2.5. The OC content was determined using the standard Walkley and Black's oxidation method [12] and organic matter (OM) was computed by multiplying the organic carbon (OC) value with a constant 1.724. Electrical conductivity meter was used to measure the EC of saturated extract of the soil [12]. TN was determined by Kjeldahl standard method [18].

According to [12], the concentration of Na and K was determined by flame photometer apparatus whereas Ca and Mg were determined by atomic absorption spectrophotometric techniques. CEC was determined on the basis of displacement after washing procedure using ammonium acetate [17]. Available phosphorus was determined using Olsen's method [12,19]. $CaCO_3$ was determined using titrimetric method with acid [20] and base saturation (BS%) was calculated by dividing the sum of extractable bases (Ca^{2+}, Mg^{2+}, K^+, and Na^+) by

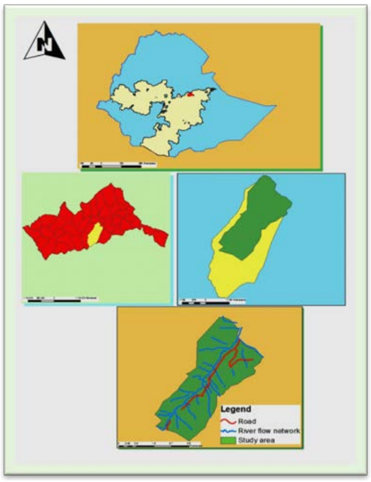


Figure 1: Location map of the study area.

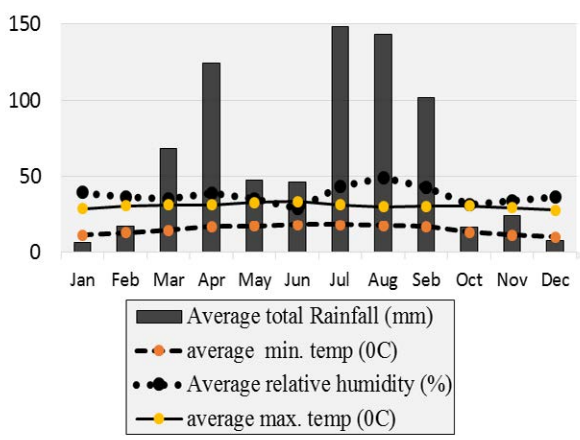
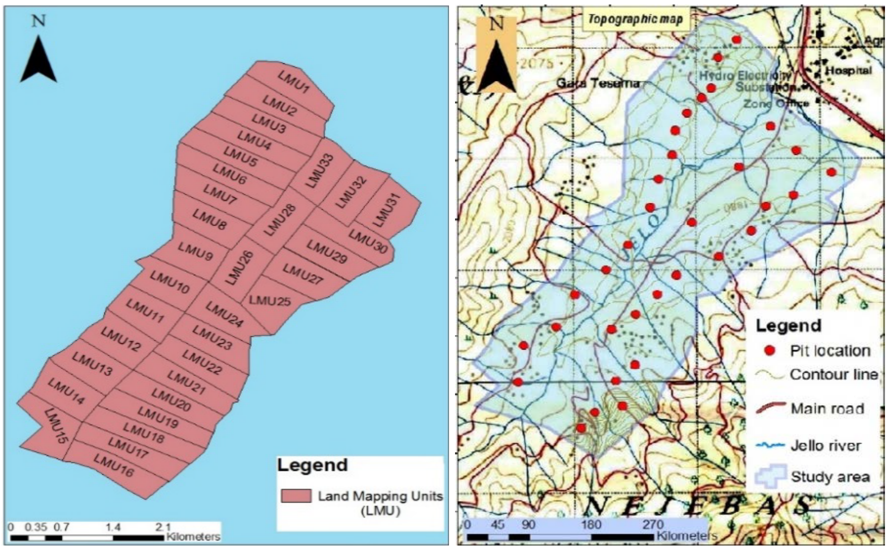


Figure 2: Climatic data.



a) b)

Figure 3: LMUs (a) and pit locations (b) of the study area.

cation exchange capacity (CEC) and multiplying it by 100 [21,22]. Exchangeable sodium percentage (ESP) was calculated by dividing the exchangeable Na to measured CEC values and multiplying it by 100 [12,15,21].

Land evaluation process: After assessing the suitability of the land for general cultivation use, the land evaluation (LE) process was proceed based on the maximum limitation method in terms of FAO's framework comparing the LCs or LQ values of each LMU with the requirements of the proposed LUT (maize, sorghum, and wheat) to identify the actual qualitative land suitability depending on physical environment data generated from topographic features, current soil characteristics, wetness condition and growing period climate data. The LE process comprised of computing the LCs values, suitability classification and land suitability mapping.

Computing the LCs values: The collected LCs data were processed and converted in to applicable LCs values (data base) using simple statistical approaches [23]. Climatic parameters during the crop growing cycle (for annual crops) was considered and an average value was calculated. In addition, the soil characteristic values changing with depth were also recalculated as depth weighted average over the 60 cm soil depth using three sections of equal thickness (20 cm) with a proportional weighting factors of 1.50, 1.00 and 0.50 from depth correction indices table (Van Ranst and Ann Verdoodt, 2005).

Depth correction

0-30cm: 0-20cm ⇒ 1.5×(20-0) =30

20-30cm ⇒ 1×(30-20) = 10

Sum= 40

30-60cm: 30-40cm ⇒ 1×(40-30) = 10

40-60cm ⇒ 0.5×(60-40) =10

Sum= 20

Therefore, the recalculated depth weighted average soil characteristic values over the total 60 cm soil depth was calculated by dividing the summation of the product of depth correction and soil characteristic value from 0-30 cm and 30-60 cm soil depths by the total depth (60 cm).

Suitability classification: Once the database was created and prepared, for each LCs values layers were made using GIS (Figure 4a). For the accomplishment of GIS assisted land suitability evaluation, querying analysis (attribute queries) was used based on the attributes of every LMU to generate individual land suitability classification (LSC) for each LCs values/layers separately in reference to the suggested crop-specific requirement. After merging the individual LSC layers using the GIS Merge window, the overall LSC was assigned for each LMU by its most limiting characteristics (Figure 4b).

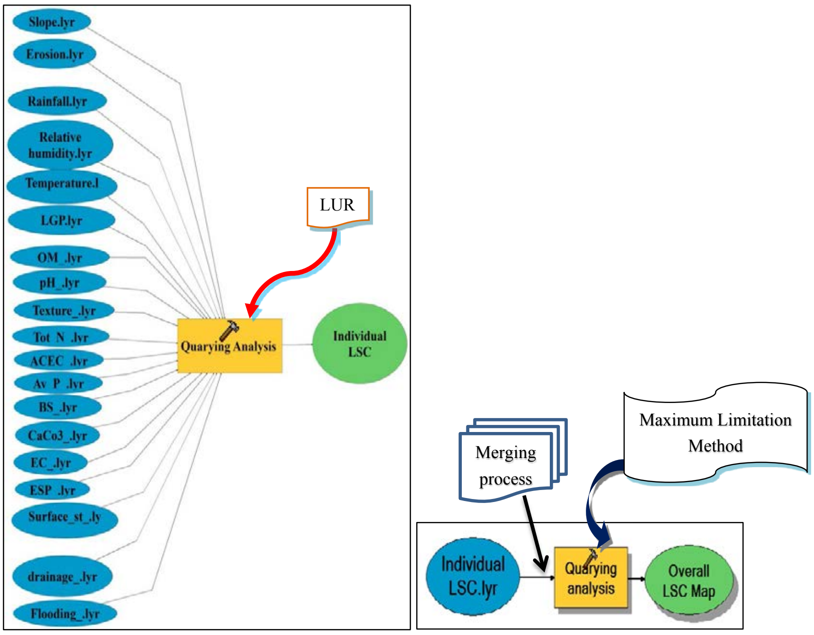
Suitability mapping: As an output, the land suitability map of the study area was displayed and shown on individual, transparent maps using different colors to indicate the suitability classes which had all its corresponding land qualities and land characteristics in its attribute table with the help of ArcGIS (Figure 4). Comparison was accomplished between the findings from this study and what is being practiced today to select relatively the better land use option.

Results and Discussion

Diagnostic LCs with set of values is illustrated in the table below for every LMU (Table 1). The soil characteristics values explained were the recalculated depth weighted average values. The deep rooting depth of representative soil profiles was measured to be more than 100cm for all LMU, which was treated as the ideal depth for annual crops as described by [12,13].

Land suitability evaluation for general cultivation

LMU32 (50 ha) is the only one assigned as highly suitable (S1); LMU1, 6, 7, 8, 18, 23 and 28 (350 ha) were grouped under moderately suitable (S2) class; nineteen (950ha) LMUs were classified as marginally suitable (S3) class and LMU2, 9, 14, 16, 17 and 19 (300 ha) were not suitable (N) due to fertility status and slope condition for cultivation purpose in general.



a) b)

Figure 4: (a) GIS model used for individual LSC and (b) overall LSC.

LMU	Soil texture class	ESP %	EC dSm^{-1}	$CaCO_3$ %	CEC Cmol/kg	OM %	Av. P ppm	TN %	pH H_2O	BS %	Slope %	Drainage class	Flooding risk	Surface stoniness, %
1	SCL	5.9	0.1	5.4	57	2.49	1.75	0.13	7.5	75.2	5-8	Well	Nil	3
2	Sandy loam	7.72	0.1	5.3	47.6	0.45	0.49	0.04	7.1	82.4	8-15	Well	Nil	3.5
3	SCL	7.27	0.25	7.4	56.9	1.15	0.88	0.11	7.23	71.3	3-8	Well	Nil	12
4	SCL	7	0.17	4.8	49	0.65	1.27	0.05	6.93	79.9	3-8	Well	Nil	4.2
5	SCL	6.9	0.09	3.4	49.6	1.51	1.09	0.08	7.07	87.4	3-8	Well	Nil	10
6	Loam	10.29	0.18	5.13	43.5	1.99	3.3	0.14	7.73	87.6	3-8	Moderate	Nil	2.1
7	SCL	7.74	0.14	2.97	43.9	2.65	1.64	0.07	7.47	70.2	8-15	Well	Nil	2
8	SCL	6.16	0.26	6.6	56.5	3.32	2.56	0.12	7.33	83.1	3-8	Well	Nil	0.2
9	Sandy loam	8.34	0.14	3.87	41.5	0.53	0.5	0.05	6.97	71.8	5-8	Well	Nil	1
10	Sandy loam	6.73	0.11	7.7	45	2.22	1.83	0.13	6.97	92.1	3-5	Well	Nil	3.4
11	SCL	6.17	0.21	4	56.9	2	2.27	0.2	7.5	45.2	5-8	Well	Nil	4
12	SCL	6.48	0.15	3.87	52.2	1.96	1.56	0.12	7.27	64.8	8-15	Well	Nil	5.7
13	Loam	5.35	0.28	6.6	54	3.59	7.19	0.19	7.17	64.9	3-8	Moderate	Slight	8.2
14	SCL	9.65	0.14	4.47	46	1.14	3.52	0.08	6.93	77.7	>15	Well	Slight	9
15	SCL	12.38	0.21	8.4	41.8	3.38	4.22	0.15	7.1	81.2	3-5	Well	Nil	4.6
16	SCL	6.97	0.15	4.9	49.7	3.15	7.17	0.14	7.07	72.1	>15	Well	Nil	2
17	Clay loam	6.24	0.21	8	61.3	1.27	1.99	0.07	6.97	82.8	>15	Moderate	Nil	2.5
18	SCL	6.48	0.29	6.3	53.6	2.85	8.39	0.13	6.77	86.2	8-12	Well	Nil	3
19	Loam	4.61	0.14	9.03	61.8	3.59	5.81	0.13	7.3	78.9	>15	Moderate	Nil	2.9
20	Loam	7.09	0.16	3.6	47.8	2.31	7.07	0.12	7.57	78.1	8-15	Moderate	Nil	4.8
21	SCL	6.3	0.12	9.53	57.6	2.54	4.33	0.53	7.13	84.3	8-15	Well	Nil	5.2
22	SCL	8.13	0.07	11.27	43.1	2.87	4.8	0.14	7.73	89.9	3-5	Well	Nil	6
23	SCL	7.74	0.2	4.8	52.9	2.53	7.12	0.77	8.13	75.9	3-5	Well	Nil	2.8
24	SCL	6.05	0.1	4	43.6	2.93	7.33	0.59	6.93	88.9	3-8	Well	Nil	7.4
25	Clay loam	7.64	0.24	7.13	50.4	3.57	5.9	1.32	7.73	90.8	8-10	Moderate	Nil	4
26	Loam	6.21	0.14	6.5	53.5	3	5.9	1.13	8.13	69.1	5-8	Moderate	Nil	4.5
27	Clay loam	8.61	0.16	4.6	42.2	2.71	4.73	0.67	7.93	84.8	8-10	Moderate	Nil	12
28	SCL	8.07	0.12	6.1	52.1	2.87	5.83	0.54	7.37	83.8	3-8	Well	Nil	2.5
29	SCL	12.28	0.1	5.9	39.7	3.47	7.47	0.83	7.73	90.6	8-15	Well	Nil	4
30	SCL	6.69	0.12	4.8	52.6	3.34	6.9	0.67	7.8	89.7	3-5	Well	Nil	3.6
31	SCL	6.04	0.1	9.4	50.4	2.34	2	0.84	7.07	70	5-8	Well	Nil	6.2
32	SCL	5.71	0.12	6.9	49.4	2.98	3.2	1.31	7.04	88.6	0-3	Well	Nil	2.9
33	Clay loam	7.8	0.11	6.2	52.8	3.25	4.07	0.86	6.7	74.9	0-3	Moderate	Nil	3.4

Remark: "SCL"= Sandy clay loam

Table 1: The recalculated depth weighted average soil characteristics values.

Individual LSC for each LCs

On the bases of individual LCs values, a separate class was rated (except for the rooting depth />100cm/ and temperature assigned as S1 concerning the three LUT; rainfall labeled as S1 for sorghum, S2 for wheat and maize; relative humidity was allocated as S2 for maize and sorghum).

Suitability ratings for wheat: Individual LCs were examined for wheat, accordingly the suitability percentage are shown in Figure 5. Suitability ratings for maize: In a similar way, individual LCs values were also matched with the requirement of maize. The suitability percentage is shown in Figure 6. Suitability ratings for sorghum: Individual LCs suitability percentage is also shown in Figure 7.

Overall land suitability classification

In general, land suitability classification of the mapping units centered on the most limiting land characteristics was classified and labeled into different suitability classes using the GIS quary builder technique (Figure 8). The overall suitability map for each LUTs was presented as an output after merging the individual LSC layers acquired. Overall land suitability classification for wheat: The overall suitability class of the study area for wheat cultivation was generally grouped into three ratings (Figure 9a) as moderately suitable (S2); marginally suitable (S3); and not suitable (N). Soil fertility, topographic feature, surface stoniness in conjunction with rainfall (LMU23 and 30) and pH (for LMU23) were considered as the limiting factors in general.

Overall land suitability classification for maize**:** The interpretation from the overall suitability map (Figure 9b) generated with the help of GIS tools shows that, no LMU was assigned as moderately suitable for maize production. The restrictive factors inducing the two suitability class (S3 and N) assigned were owed by the soil fertility status, pH and topographic factors.

Overall land suitability classification for sorghum: Similarly, the overall suitability class for sorghum cultivation falls under marginally suitable (S3) and unsuitable (N) (Figure 9c). The suitability class was brought by the dominant limiting factors as soil fertility, topographic condition, RH, together with textural class (for LMU2, 9 and 10), surface stoniness aimed at LMU13 and pH for LMU23 and 26. Concerning the three land utilization types, non-suitability class (N) was also observed as a mutual rating for 800ha (48% or LMU1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 14, 16, 17, 19 and 31). LMU25 and 27 were assembled to be marginally suitable for maize and wheat. For that of maize and sorghum, there was also 100 ha (LMU23 and 30) grouped under marginal suitability (S3). As far as the suitability map of wheat and sorghum was referred;

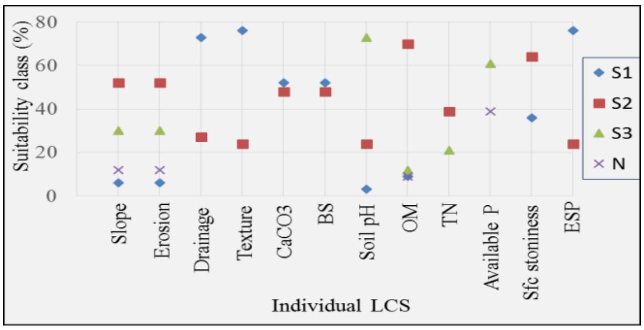


Figure 5: Individual LSC percentage for wheat.

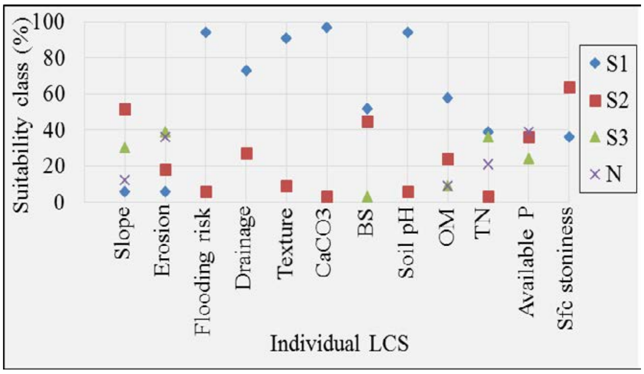


Figure 6: Individual LSC percentage for maize.

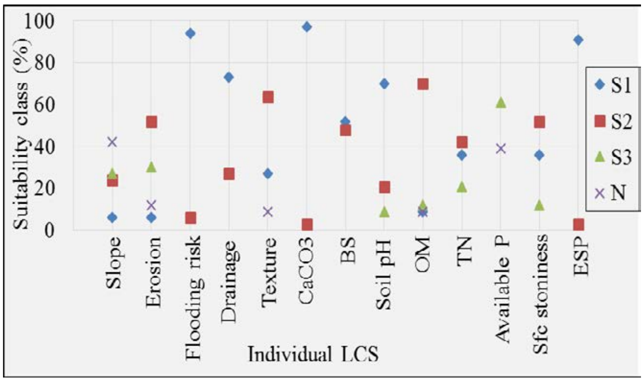


Figure 7: Individual LSC percentage for sorghum.

LMU18, 20, 21 and 29 (200 ha) was unsuitable (N) for both LUTs. The outcome of this study also tells that none of the thirty three LMU falls under highly suitable (S1) class.

Currently, farmers on the entire watershed cultivate maize and sorghum (more dominantly) intercropping with chat. According to the comparison made between the existing land use being practiced and the findings from this study, 800 ha (48%) and 1100 ha (67%) area of land was mismatched (currently not suitable) for maize and sorghum cultivation respectively.

Based on the analysis, wheat cultivation is relatively better (moderately suited) than the land use being practiced (maize and sorghum) on the bases of the present situation for 100 ha (LMU23 and 30). Comparatively maize cultivation is the other option (it is marginally suited) for LMU18, 20, 21 and 29 (200ha) and wheat or maize is better on LMU25 and 27 (100 ha) rather than sorghum cultivation at present. On the other hand, none of the three land utilization types are suitable for 800ha or 48% of the total area.

The continuing of existing land use (LU) practices beyond the natural ability of the land had been considered as a catalytic agent for the exponential depletion of the present scarce soil resource, the low soil fertility status for instance. The nonstop expansion of agricultural practice was the driving force for the decline of forest area and in some parts of the surveyed area long and steep slope is used for cultivation purposes.

Concurrently unless and other wise measures are taken, these

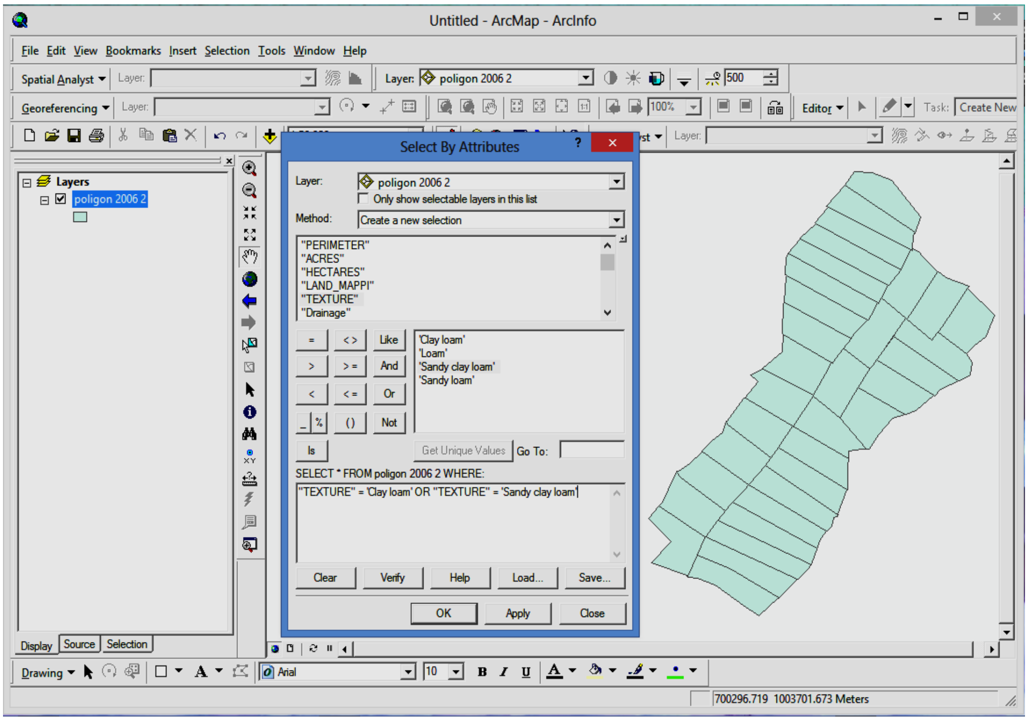
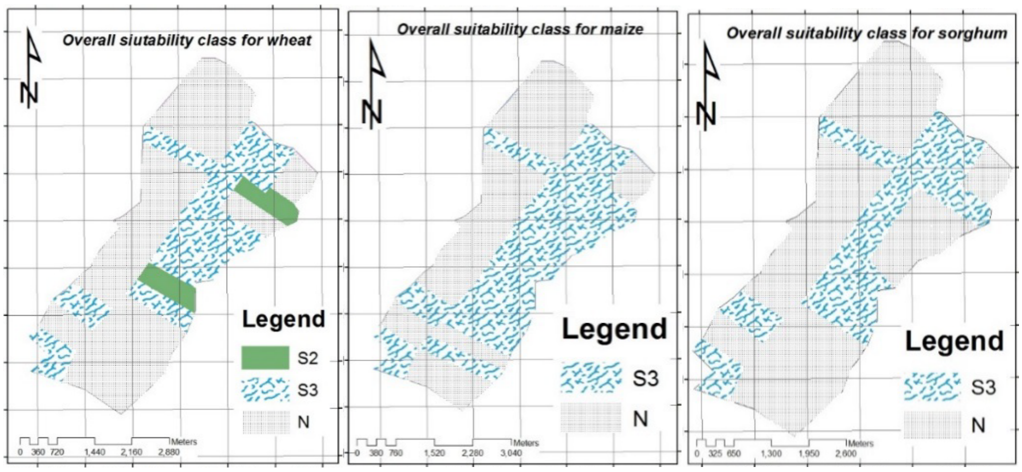


Figure 8: Quarying analysis window used.



(a) (b) (c)

Figure 9: (a) Overall land suitability map for wheat, (b) maize and (c) sorghum.

augment soil erosion, resource degradation and adverse changes in river regimes (for instance, frequent flooding and absence of dry season stream flow) leading to irreversible degradation without hyperbole.

Conclusion

Currently, the surveyed area was assembled into three suitability classes as moderately suitable (S2) for 6%, marginally suitable (S3) for 33% and 61% unsuitable (N) for wheat. On the other hand two suitability classes were observed for maize (52% and 48%) and sorghum (33% and 67%) cultivation as marginally suitable (S3) and unsuitable (N) respectively. From the overall suitability ratings attained, presently none of the thirty three land mapping units fell under highly suitable (S1) class to any of the three land utilization types. Based on the individual LCs, exceedingly available P (named as the most severe limiting factor) of the soil was the only one responsible for not to be characterized as high suitability (S1). Therefore, major limiting land characteristic for crop production in the district had been the low fertility status of the soil attributed to the low amount of available P. This also indicates that such lands can be degraded and easily loose the productive potential if the existing land use practices are ongoing and no well-timed appropriate measures are undertaken.

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