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ORIGINAL RESEARCH PAPER

Irrigation site selection using hybrid GIS-based approach

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ABSTRACT

BACKGROUND AND OBJECTIVES: The use of traditional site selection methods for potential irrigation schemes is so common in Malawi. The overdependence of these methods has had significant consequences on the environment such as pollution, siltation, and land degradation and soil erosion. Traditional selection of irrigation sites is a complex task which is time-consuming, costly and involves collection of a lot of data sets. However, advances in Geographic Information Systems present an opportunity to easily integrate complex systems involving a lot of data sets. The objective of this study was to identify potential areas for irrigation farming in Kasungu district in Malawi using hybrid spatial datasets.
METHODS: Multi criteria decision analysis approach was used in Arc GIS 10.8 to analyze datasets such as slopes, rivers, land use, soil types, soil depths, water quality, water quantity and drainage patterns. A questionnaire was used to solicit expert views on factors to consider when siting feasible irrigation areas.
FINDINGS: This study observed that the use of Geographic Information System in irrigation site selection is flexible and time efficient due to its ability of handling complex and huge volume of datasets. Moreover, the produced maps enhanced an easy understanding of the identified areas hence providing an aid to making right decisions in environmental management. The study found that in Kasungu district, 36.9% of the land is highly suitable, 20.7% is moderately suitable, 33.1% is lowly suitable and 9.3% is not suitable for irrigation.
CONCLUSION: This paper provides good information on promoting the utilization of GIS to solve site selection problems in a bid to reduce soil erosion, pollution and improve land management. The study recommends the promotion of using GIS in government agencies for better decision-making in sustainable irrigation development. The scientific approach used in this study can also be extrapolated in the assessment and evaluation of water resources in Malawi.

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INTRODUCTION

Unlike most developed countries, most African economies still depend on rainfed agriculture as the main source of water for crop production. Due to climate change, there has been a shift from rain-based farming to irrigated farming which enables farmers to grow more than twice in a year. Because of rainfall unpredictability and frequent weather shocks, small scale irrigation farming has long been recognized as a leeway to mitigate these maladies in addition to supplementing food availability (Kadyampakeni *et al.*, 2018). Though its recognition is valuable, irrigation has been limited by some constraints such as global climate change, drought, insufficient and unevenly distributed rainfall, and population increase (Boateng *et al*., 2016; Park *et al*., 2019). Kumbuyo *et al*., (2014) argue that the major problem associated with the rainfall-dependent agriculture in Malawi is the high degree of rainfall variability. Due to this variability, crop failures due to dry spells and droughts are frequently leading to food insecurity affecting the livelihoods of the people (Bae *et al*., 2018; Mulwafu *et al*., 2002). In areas with insufficient rains, Mailhol *et al*., (2004) assert that irrigation provides an effective and efficient way of supplying water for agricultural production. However, in Malawi, irrigation has not been fully developed despite the recognition by government of its significance for enhancing economic development (Mulwafu *et al*., 2002). A good example is the GreenBelt Initiative (GBI). The National Irrigation Policy (NIP, 2016) expounds that water shortages, land disputes and por maintenance are among the crucial challenges affecting irrigation development in Malawi. Djagba *et al*., (2014) noted that most organizations and government departments still use the traditional approach in irrigation site selection. This approach involves collecting a lot of datasets which is time consuming and costly. This approach can easily lead one into ignoring other important variables on site selection for irrigation. Processing of such data is equally untimely and in other cases inefficient and ineffective. This has often resulted into frequent problems in irrigation schemes due to improper site selection. Agricane Malawi (2009) agree with Kadyampakeni *et al., (2014*) that constraints to irrigation development in the Malawi have been due to lack of technical expertise in irrigation, use of poor agricultural practices and poor site selection methods. The effect of not considering proper site selection procedures is significant and often leads to problems related to soil erosion, water management, seepage, poor drainage, siltation, flooding, poor marketing systems, insufficient water, and poor yields. These problems are evident in some schemes such as Luweya, Nkopola and Khanda. This substantiates studies of FAO (2002) and Nhira *et al*., (2008) which noted that most problems in irrigation schemes arise from poor site selection methods. Economically, poor site selection can lead to spending much money on rehabilitation, a problem that could easily be solved if necessary tools were used (Schuenemann *et al.*, 2018). Contrary to traditional approaches, Varvani (2018) highlighted that GIS-based systematic approaches to siting places for developmental activities are cost effective and enables catchment management. Advancements in technology have led to the introduction of Geographical Information Systems (GIS) which has been used in many sectors to aid decision making in site suitability analysis (Jha *et al*., 2014; Cech, 2002; Malczewski, 2004). For example, using the analytical capabilities of GIS, (Mahmoud *et al*., 2015 delineated suitable sites for rainwater harvesting feasible for water supply and irrigation projects. Most studies (Bhagat, 2016; Delgado *et al*., 2015; Garede *et al*., 2014; Modela *et al*., 2017) have highlighted that GIS is a powerful tool for scientific investigations, resource management, development planning, land evaluation, site selection and as a Decision Support System (DSS). Despite the advances of GIS technology worldwide, the use and application of GIS in irrigation development in Malawi in still limited. To the best of our knowledge, Malawi has no much record and/or has little literature concerning the use of Multi Criteria Decision Analysis (MCDA) approach for site selection in irrigation. In an endeavor to improve irrigation site selection methods for improved water management, this paper sought to site potential irrigation sites in Kasungu district, Malawi, using MCDA in June, 2020.

MATERIALS AND METHODS

Description of the study area and context

Kasungu district is found in Central region of Malawi. Fig. 1 shows the location of the study area. The district is found on latitude 13°1'59.99''S and longitude 33°28'59.99''S. The district is on the Lilongwe Kasungu plain and is approximately 127 kilometers from the capital city of Malawi, Lilongwe.

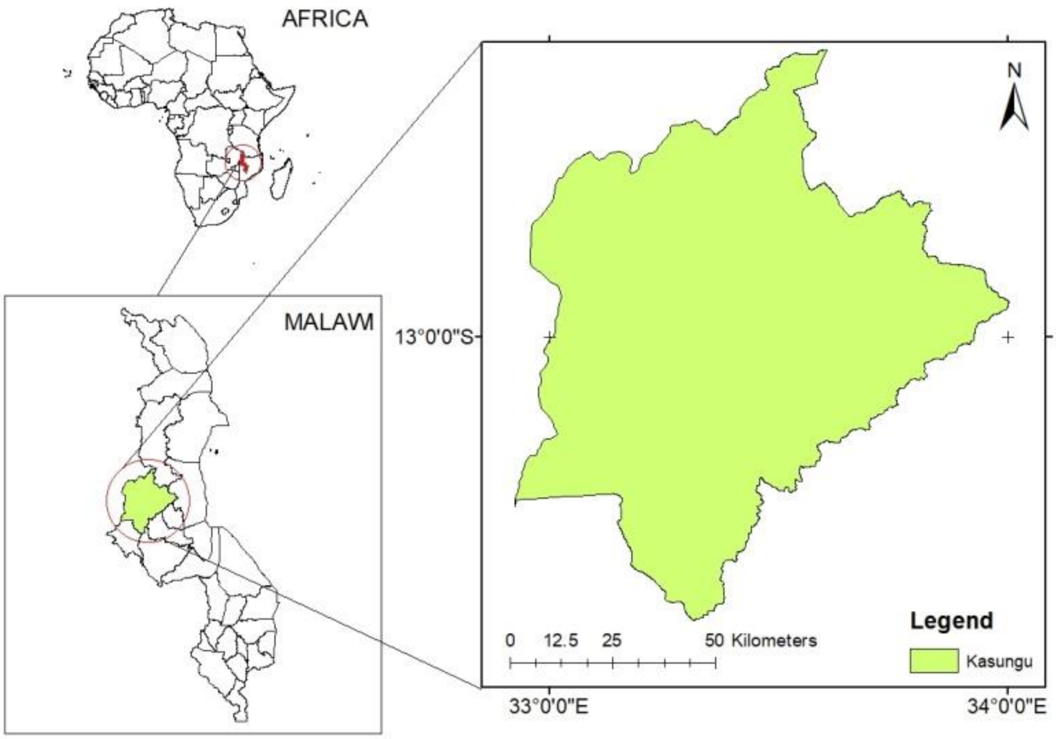

Fig. 1: Geographic location of the study area in Kasungu district

The área of Kasungu district is approximately 7830 km^2 covering 8 percent of the country.

Development of the model

This study used a multi criteria decision analysis (MCDA) approach to identify different levels of suitable sites for sustainable irrigation development. Hussein *et al*., (2019) highlighted that multi-criteria land suitability analysis enables sustainable use of scarce resources such as water and land.

The approach is shown in Fig. 2.

Spatial datasets used in this study were reclassified in order to come up with a common measurement scale for easy identification and suitable area determination. FAO (2002) guidelines in addition to expert advice were referred to in weighting analysis. A questionnaire was used to determine the factors which irrigation experts consider when siting an área for irrigation. The study used a scale of 1 to 4 with 4 being the most suitable and 1 not suitable. Table 1 shows the suitability reclassification levels that were used to determine the suitable areas for irrigation development.

These parameters were weighted in order to determine their level of influence in decisión making. The Analytical Hierarchy Process (AHP) was used to weigh and validate the parameters as proposed by Saaty (2008). Saaty (2008) recommended the usage of weighted parameters when the consistency ratio (CR) was less than 0.1.

RESULTS AND DISCUSSION

Fig. 3(a) shows the elevation of Kasungu district. The district has a peak elevation of 1616 metres above sea level and the lowest point is 774 metres above sea level. The northern part of the district is on a higher land than most of the central part which is flat. Fig. 3(b) presents the distribution of various slope classes of Kasungu. The district is predominantly (54.4%) flat with slopes of 0-2%. These slopes are ideal for irrigation. Sloping land (37.8%) has a percentage of 2-7%, moderately steep land (5.8%) range from 7-16% and steep land (1.6%) ranges from 16-32% whereas very steep lands (0.4%) are greater than

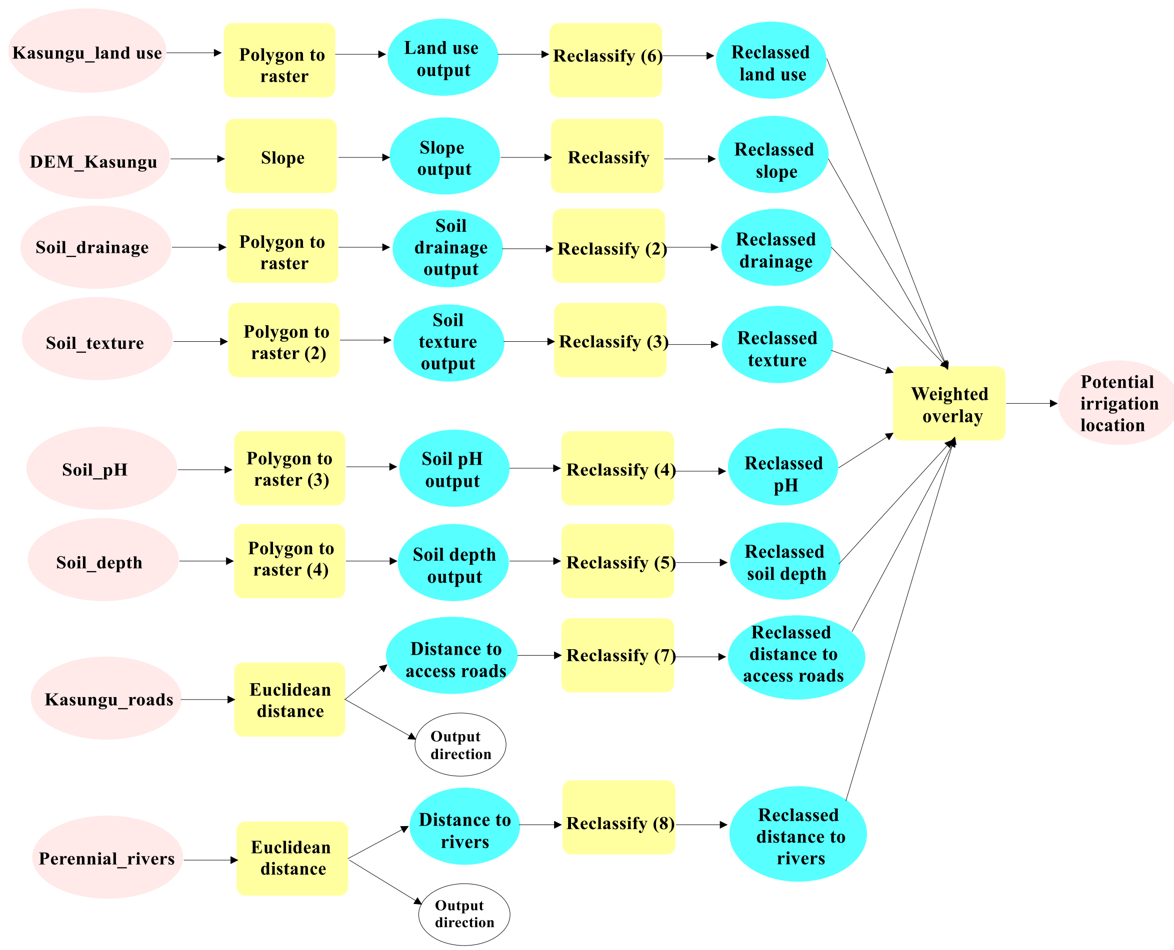

Fig. 2: Irrigation suitability model in Model Builder

32%). FAO (2002) recommends slopes of less than 2% to be feasible for irrigation development especially surface irrigation systems which are common among smallholder farmers. It is an important management tool when deciding when to use gravity fed irrigation methods or pumping. This observation agrees with Maina (2016) that slope has a direct impact on runoff, erosion and drainage in the development of an irrigation scheme. Fig. 3(b) therefore suggested that the district is relatively flat, an attribute which is of prime importance when selecting irrigation sites and methods.

Fig. 3(c) displays the drainage regime in the district. The results indicated that 96.8% of the disrict has good soils with good physical properties that allow the wáter to drain properly. This concurs with Fig. 3(f) indicating that most parts in the district are not susceptible to flooding. This could be attributed to well drained soils and slight levels of erosion in the district. Areas which are prone to flooding have poor drained soils and have high rates of erosion hence not feasible for surface irrigation systems which are common in Malawi. This agrees with Tadesse (2010) who noted that flooding is due to poor drainage, high rates of deforestation and soil degraded areas. The Therefore, the good drainage regime in the district would facilitate the proper siting for a feasible irrigation área and further aid engineers to design sustainable drainage channels in irrigation schemes. Fig. 3 (d) shows that the district has a dendritic riverine system with direction of flow from the west to the east in Kasungu. The district has a network

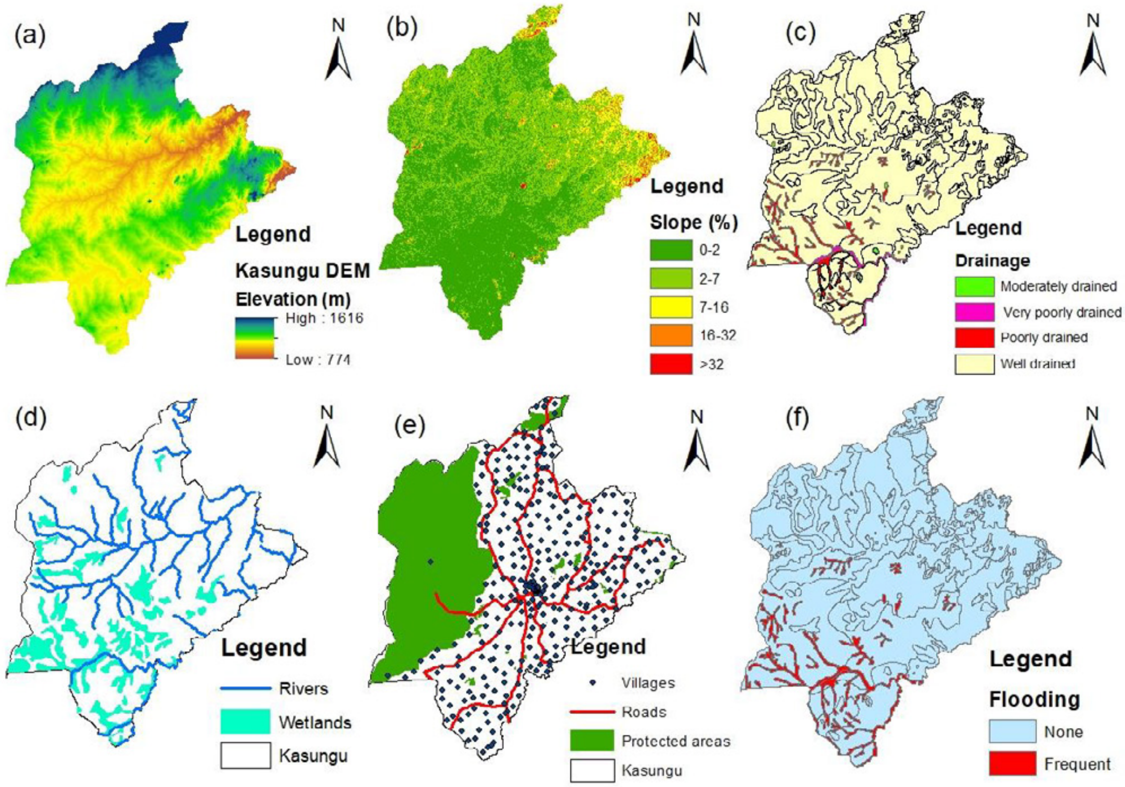

Fig. 3. Digital Elevation Model, slopes, drainage systems and flood frequency in Kasungu district

of perennial rivers such as Dwangwa, Bua, Lingadzi, Rusa, Luwelezi, Lupache and Milenje which have good water quality. The results indicated that the minimum dry season flow (Q80) ranged from 0.01 to 0.2 l/s/km^2. In conjunction with Fig. 3(b), many areas have an opportunity to be irrigated by many methods of irrigation. The flow morphology also presents a chance for rainwater harvesting technologies in the district hence providing a storage means for irrigation water. This could also help in the mapping of the potential areas for irrigation when these rainwater harvesting sites where flow accumulates more have easily been identified. Fig. 3 (e) displays the protected áreas comprising of national parks and forest reserves, and road networks in Kasungu district. Many parts of the district are accesible due to good road networks hence presenting an opportunity for easy access to markets. FAO (2002) asserted that road networks are very important when siting an irrigation land for easiness of scheme accessibility, labour accessibility and transportation of farm inputs and outputs. Table 1 considered feasible closeness of roads to a suitable irrigation area. As noted by Andersson *et al.*, (2009), in small land holdings, areas close to the river or roads are highly suitable for development than those which are at a distance. The respective soil properties considered in this study were soil type, soil depth, soil pH, and colour as shown in Figs 4 and 4(a) showed that most soils in the district have the acceptable range of acidity and alkalinity of 5.5 to 8.0 for most crops. Soils which are highly acidic or highly alkaline normally decrease crop yields and not good for irrigation. Fig. 4(b) exhibited that the predominant soils in the district are loamy sand, sandy clay and sandy loam. Fig. 4(c) indicated that the district is dominated by deep soils within the range of 100 cm and greater than 150 cm. This is the most effective root zone depth for most crops. Fig. 4(d) indicates the soil colour for the district. This attribute is related to the distribution of organic

Table 1: Suitability class levels for irrigation development in Kasungu district

Spatial dataset	Suitability reclassification level		
	Class (%)	Weight	Description
	0 - 2	4	Highly Suitable
Slope	2 - 7	3	Moderately Suitable
	7 - 16	2	Lowly Suitable
	More than 16	1	Not Suitable
	Class (cm)	Weight	Description
	>150 (Very Deep)	4	Highly Suitable
Soil depth	100 - 150 (Deep)	3	Moderately Suitable
	50 - 100 (Moderately Deep)	2	Lowly Suitable
	0 - 50 (Shallow)	1	Not Suitable
	Class (cm)	Weight	Description
	>150 (Very Deep)	4	Well drained
Drainage	100 - 150 (Deep)	3	Moderately drained
	50 - 100 (Moderately Deep)	2	Poorly drained
	0 - 50 (Shallow)	1	Very Poorly drained
	Class	Weight	Description
	Loamy sand	4	Highly Suitable
Soil texture	Sandy loam	3	Moderately Suitable
	Sandy Clay	2	Lowly Suitable
	Sand	1	Not Suitable
	Class (pH)	Weight	Description
	5.5 – 7.0	4	Highly Suitable
Soil PH	7.0 – 8.0	3	Moderately Suitable
	4.5 – 5.5	2	Lowly Suitable
	> 5.5	1	Not Suitable
	Class range (km)	Weight	Description
	0 – 1.5	4	Highly Suitable
Distance to perennial rivers	1.5 - 3	3	Moderately Suitable
	3 - 4.5	2	Lowly Suitable
	More than 4.5	1	Not Suitable
	Class (km)	Weight	Description
	0 - 1	4	Highly Suitable
Distance to access roads	1 - 2	3	Moderately Suitable
	2 - 3	2	Lowly Suitable
	More than 3	1	Not Suitable

manure in the soil. Black or brown soils normally are rich in organic manure, are fertile and are suitable for arable crops. This is one of the soil's characteristic of Kasungu-Lilongwe plain. The correct siting of these areas would hence improve the incorporation of sustainable and effective irrigation to improve the livelihood of the people in the area. Fig. 4(e) shows the land use/cover patterns in Kasungu district. Most land (55.11%) is arable, 22.42% is covered with forests, and 21.87 % is covered with wetlands and dambos whilst the remainder is used for settlements. A careful examination in the cultivation land revealed that not all the cultivation land is irrigable. This was because some areas were very far from potential water sources. These areas present an opportunity for rainwater harvesting for agriculture. This is in line with FAO (2002) which highlighted that the process of land use/cover classification is the appraisal and grouping of specific areas of land in terms of their suitability for defined uses. Fig. 4(f) pinpoints landforms where most flat uplands are the mostly cultivated áreas. The landforms reveales that the district has a weathered basement aquifer lithology that provides groundwater yields within the range of 0.05 to 0.62 litres per second. The district also has a rich network (16.9%) of dambos which feasible for small scale irrigation. The outputs from these landforms suggested that irrigation is feasible in most parts of the districts.

Fig. 5 highlights the criteria weights that were

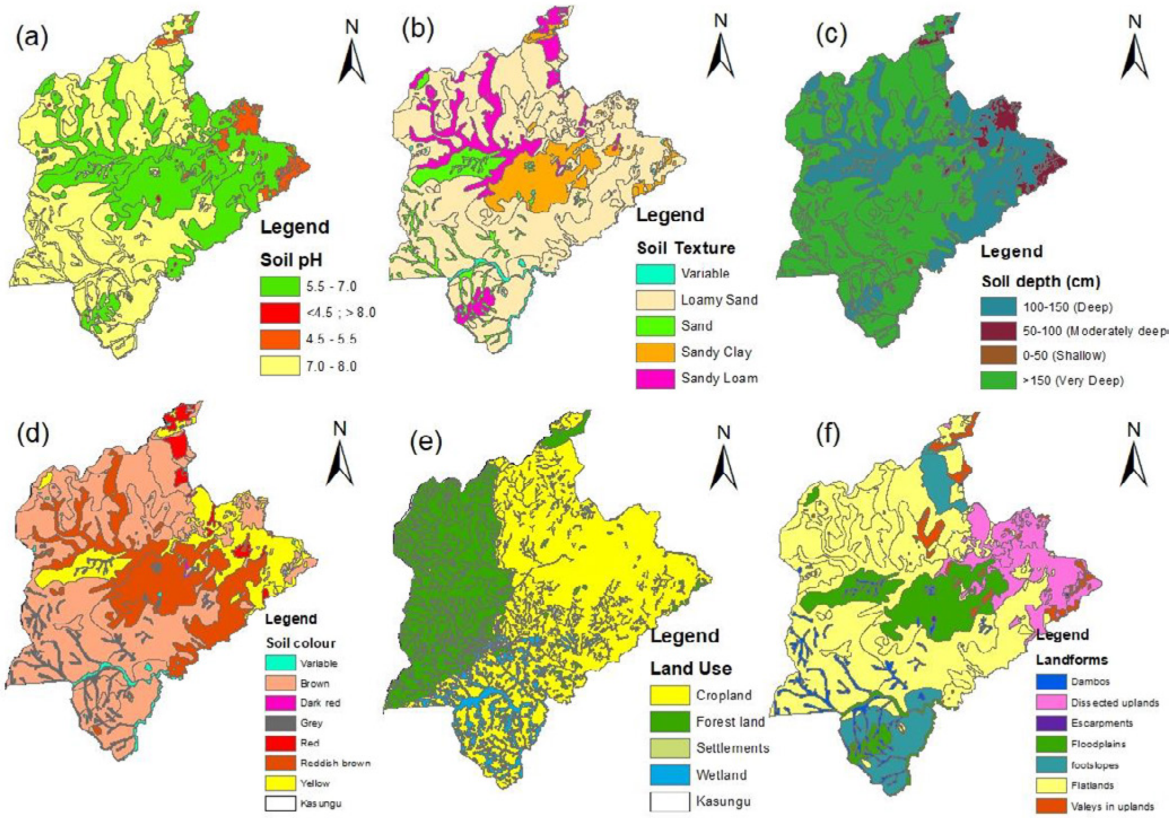

Fig. 4: Soil characteristics, Land uses and Land forms in Kasungu district

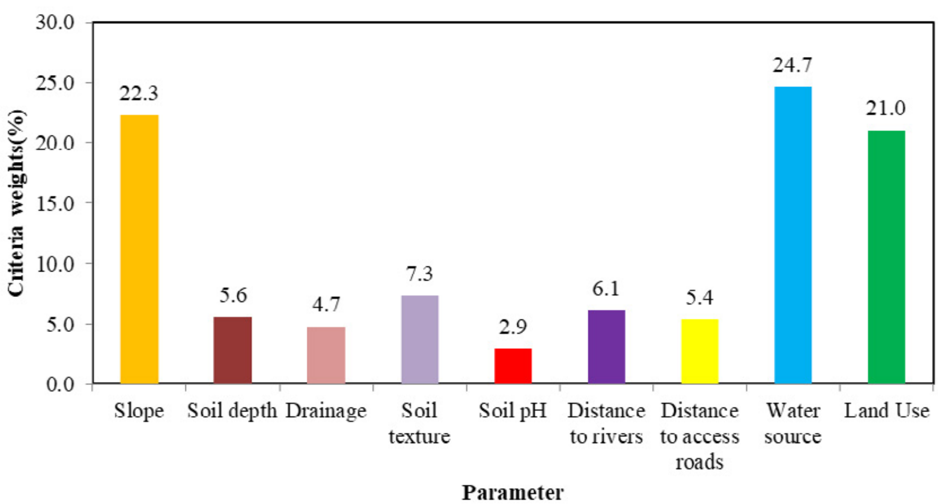

Fig.5. Criteria weights of irrigation site selection parameters

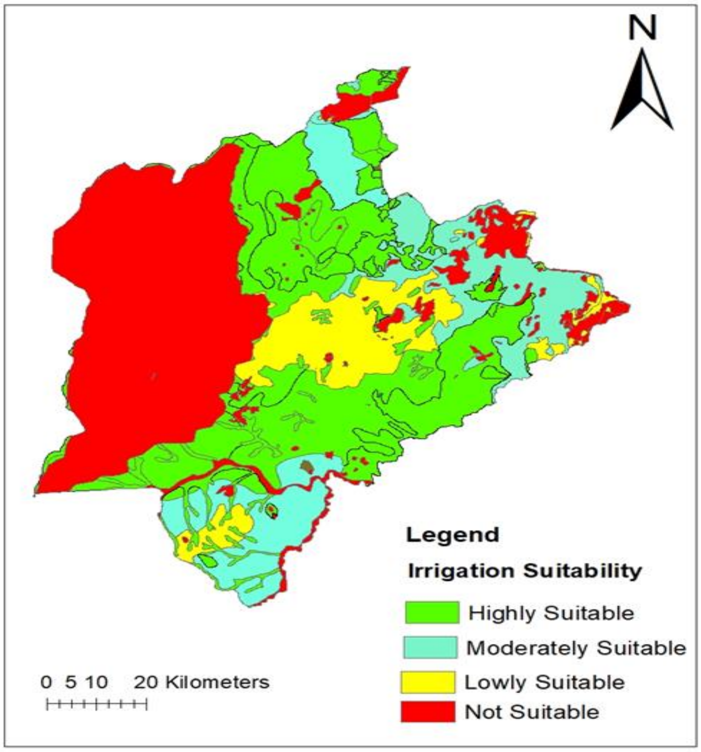

Fig. 6: Irrigation Suitability Levels in Kasungu

used to determine the level of influence of each parameter. These weights were dependable as the consistency ratio (CR=0.09) was less than 0.1 as recommended by Saaty (2008).

The results indicated that wáter source, slope and land use had significant influence in siting a feasible irrigation área. However, soil type, soil depth and distance to the wáter sources were also crucial in decisión making. The AHP approach employed in ArcGIS revealed best areas for irrigation in Kasungu district. The feasible irrigable areas were the ones showing an intersection of all the variables utilized, not only being the ones present, but also as of great importance and significance where irrigation is influenced. Fig. 6 shows suitable irrigation sites with different suitability levels. It was observed that 36.9% is highly suitable, 20.7% is moderately suitable, 33.1% is lowly suitable and 9.3% is not suitable for irrigation. Similar to Girma *et al*., (2019), the findings showed that GIS-based results aid decision makers to easily understand and visualize results. The suitability map enhances an easy and quick identification of best sites thereby aiding easy decision making. This further reinforces the observation of Mbilinyi *et al*., (2007) that GIS is a great tool in deciding sites for developmental projects. The processing of the data was timely harmonizing the notion of Raza (2018) that the use of satellite data and its processing using Remote Sensing and GIS saves time and helps in the identification of best sites for developmental projects. The findings as seen in Fig. 6 would easily guide irrigation engineers on the best irrigation systems to propose depending with the suitability level which would enhance sustainable irrigation systems. This concurs with the assertions of Rasooli (2015) and Kavurmaci (2019) that site suitability maps enhance the development of sustainabe water infrastructure and investment plans.The áreas which were not suitable for irrigation were protected áreas, áreas prone to flooding and very high escarpments.

CONCLUSION

The prime objective of this study was to identify irrigation sites using a multi criteria analysis algorithm in GIS. The study used alot of important spatial datasets such as slope, drainage, road networks, soil types, soil texture, flooding buffers, protected áreas, land forms, soil pH, soil depths and water quality. The results have revealed that when hybridization of spatial datasets is considered in irrigation site selection, best and accurate areas can easily be determined within a very short period of time. With regards to data acquisition, GIS further serves as a better data management tool so imperative in the monitoring of environmental parameters for different projects. The availability of open source software GIS application should enhance the availability and usage of GIS in agricultura projects such as irrigation site selection. Contrary to the traditional methods which have been used for sometime in Malawi, this study has illustrated that using a hybrid GIS approach is easy, time effective and accurate. This study has also provided an insight that GIS can be used as a management tool towards sustainable land management practices through the siting of best areas for development projects. The findings from this study shows that most parts in Kasungu are irrigable. This study observed that expert advice differed insignificantly to the requirements of FAO (2002). This suggests that expert advice must be referred to when siting áreas for irrigation. In the light of the above highlights, this study recommends the adoption of GIS technology by government agencies, academia, investors, Non-Governmental organizations and other stakeholders on decision making for project planning, implementation, monitoring and evaluation. This study attempted to delineate áreas feasible for irrigation in Kasungu district by means of GIS and has found that GIS is a proper tool for environmental data analysis and sequential siting of feasible irrigation areas.

AUTHOR CONTRIBUTIONS

S. R. Chikabvumbwa conceptualized, analyzed the data and prepared the manuscript. D. Sibale and S. W. Chisale aided in analysis and interpretation. All authors have read, agreed and approved the final manuscript.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

ABBREVIATIONS

GIS	Geographical Information System
MCDA	Multi Criteria Decision Analysis
GBI	Green Belt Initiative
FAO	Food Agriculture Organization
DSS	Decision Support System
%	Percent
NIP	National Irigation Policy

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