Modelling areas for sustainable forest management in a mining and human dominated landscape: A Geographical Information System (GIS)- Multi-Criteria Decision Analysis (MCDA) approach

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1. Introduction

The concept of sustainability from an ecological perspective establishes a connection between human needs and the ecosystems (Ramachandra, Setturu, and Vinay 2018). In meeting the human needs, transformation of ecosystems for production of goods and services should not compromise the carrying capacity of the affected ecosystems (Mukoni 2015). Forests constitute an important part of the terrestrial ecosystems by providing several goods and services, such as food, biodiversity, medicine, recreation and watershed for life sustenance, and provision of livelihoods to local communities (Mehring and Stoll-Kleemann 2008; Gabay and Rekola 2019). More than half of the earth’s population live around the forests and are supported by forest ecosystems (Shvidenko, Barber, and Persson 2005). About 1.6 billion people around the world depend on forests and their products for livelihoods and approximately 350 million people rely on forests only for their environmental incomes and subsistence (Mayers and Vermeulen 2002).

Forests are home to vast amounts of terrestrial and aquatic biodiversity, and they are the most species-rich habitat type on the planet, particularly in humid tropical regions (Lindenmayer 2009; Gibson et al. 2011). Human activities that result in forest loss, fragmentation, and degradation (FAO 2015) have already resulted in a significant loss of biodiversity and homogenization (Lindenmayer and Franklin 2002). The rate of deforestation is expected to increase, particularly in the rich forests of Central and South America, South and Southeast Asia, and Africa (Keenan et al. 2015). These changes in forest cover and condition are a cause for concern because they...
threaten biodiversity and a wide range of critical ecosystem services such as climate regulation, biomass production, water supply and purification, pollination, and habitat for forest species (Brockerhoff et al. 2013; Mori, Lertzman, and Gustafsson 2017).

The levels of encroachment in protected areas (PAs) caused by anthropogenic activities, such as cultivation, and urban development are degrading some protected national and local forests in Zambia (GRZ 2015). Zambia’s rate of deforestation is estimated at about 1.5% per annum (250,000 ha per annum) (Henry et al. 2011). The main drivers of deforestation are agriculture and settlements (Vinya et al. 2011). The degradation of protected forests in the North-Western Zambia, and Solwezi in particular, produces adverse impacts on wildlife habitats that are very high and alarming as this region is among the few areas in Zambia where most of its area has undisturbed forests. Protected forest areas in Zambia, and Solwezi district in particular, are facing varying degrees of human disturbance and are in several stages of forest destruction and fragmentation as a result of the presence of large-scale mining activities (GRZ 2019). Considering the significance of biodiversity in the provision of ecosystem services, widespread forest degradation is likely to have far-reaching consequences, such as reduced resistance to natural or anthropogenic disturbance (Brockerhoff et al. 2017). As a result, disturbances appear to be increasing in frequency and intensity (Brockerhoff and Liebhold 2017; Freer-Smith and Webber 2017). As such, declines in biodiversity are likely to reduce forests’ resistance to climate extremes (Malhi et al. 2020) as well as pests, pathogens, invasive species, and other disturbance factors (Jactel et al. 2017), and to reduce the provision of ecosystem services in general (Vila et al. and Hulme 2016).

The inadequate information on the state of protected forests in Zambia as a country, and Solwezi district, limit the conservation efforts (GRZ 2015), because of limited financial and technical resources for biodiversity monitoring (Lindsey et al. 2014). The process of selecting areas with high conservation potential is increasingly relying on advanced spatial data analysis, which is made possible by the development of Geographical Information Systems (GIS) (Wood and Dragicevic 2007; Ahmad, Goparaju, and Qayum 2018; Vaissi and Sharifi 2019; Bakirman and Gumsay 2020; Everest, 2021). Compared to GIS-based approaches, classic and field-based methods in assessing forests status and trends are mostly time-consuming and inefficient especially in inaccessible areas (Ahmad, Goparaju, and Qayum 2018). Problems in decision-making on spatial preferences often involve many evaluation criteria. The coupling of these multiple evaluation criteria in a spatial context has given rise to the GIS-Multi-Criteria Decision Analysis (GIS-MCDA) method (Malczewski 2006).

GIS-MCDA is considered as a set of tools and techniques for processing and merging geographical data and preferences in order to provide information for decision-making (Rahman et al. 2012; Malczewski and Rinner 2015). While GIS helps in automating, managing, and analysing a wide range of geographic data (Boroushaki and Malczewski 2010; Wang and Du 2016), MCDA on the other hand provides a wide range of approaches, techniques, and processes that assist the decision-making process (Malczewski 2006; Boroushaki and Malczewski 2010; Montrapussorn, Thaitakoo, and Banomyong 2011). The use of GIS-MCDA approach can help the decision-maker to quickly assess the state and select potential PAs while minimizing expenses and time required in the early planning stage (Phua and Minowa 2005). GIS-MCDA is increasingly being used to assess suitability (Zhang et al. 2013; Rahman, Shi, and Chongfa 2014; Sanare, Ganawa, and Salih 2015; Vaissi and Sharifi 2019; Bakirman and Gumsay 2020).

While GIS-based approaches are increasingly being used to assess the state of PAs, information on the state of PAs in Zambia is not updated due to limited financial and technical resources (Lindsey et al. 2014). However, the desire of having up-to-date information, which would assist the government to plan and manage forest resources on sustainable basis, has not been attained because of several factors such as inadequate resources, lack of inventory equipment, finances, mobility and low capacity of staff to carry out resource assessments (FAO 2005). To the best knowledge of the author, no GIS-MCDA studies have been carried out to assess the state of PAs and identify potential areas for conservation in Zambia. We postulate that GIS-MCDA approach would technically support monitoring of PAs. Therefore, this study aims at answering the following questions: (1) what is the state of PAs in the mining and human-dominated landscape of Solwezi? (2) what are the suitable forest areas for conservation in Solwezi?

2. Materials and methods

2.1. Study area

Solwezi district (i.e. town) is the provincial headquarters of North-Western Province of Zambia (12° 10’ 0.7356° S and 26° 23’ 2.3172° E) (Figure 1). It is a rapid expanding mining town, with a high uncontrolled urban development due to increasing demand for human settlements (i.e. housing). The town has recently become a busy, densely populated and rapidly expanding business
area (Negi 2014). The human population of Solwezi district was estimated at 90,856 inhabitants in 2010 and is expected to increase to almost 500,000 inhabitants by 2030 (ICED 2018; CSO 2013; ICED 2018). Human population boom, poverty and land scarcity place much pressure on natural resources and lead to growing demand for agricultural land and human settlements (ICED 2018; CSO 2013; ICED 2018). Ten kilometres north of the centre of Solwezi town is Kansanshi Mine, an open pit mine and the biggest copper mine by output in Africa (Kesselring 2017). The copper and gold mining operations began in 2005 and the copper production represents about 40% of Zambia’s total output, making it the largest copper mine in Africa (ICED 2018).

Solwezi district is home to five protected forests, which are Solwezi, Mbonge, Mutanda, Chimbe and Mulenga (GRZ 2019) (Figure 1). Mbonge protected forest area was de-gazetted by the Zambian government to establish the mining site. However, part of the land parcel of the protected forest area found in the neighbouring Kalumbila district spans across Solwezi district. Few years after the opening of the Kansanshi mine, the fragmentation of the forest has gradually increased due to the expansion of the mine (Parduhn 2017). The Kansanshi mine area used to be a habitat for a wide range of wildlife inter alia bush babies, mole rats, birds and common duikers (URS 2012). However, several thousand hectares of forests were destroyed in and around Kansanshi mine to give way to the expansion of the mining site, waste-water treatment reservoirs, processing plants, an airfield, development of a road network and human settlements.

2.2. Criteria selection and identification

Five factors based on literature and expert knowledge on the ground (Goparaju, Ahmad, and Sinha 2017; Ahmad, Goparaju, and Qayum 2018) were identified and used for the suitability analysis. The criteria are as follows: (1) land use/cover, (2) wetlands, (3) rivers, (4) slope, and (5) roads. Two restriction factors, urban area and mine area, were also identified and used in the model that constitutes the main disturbance and danger for forest area.

2.3. Data acquisition

Three datasets were used in this study: (1) processed data for wetlands, rivers and roads, downloaded from different sources (Table 1); (2) digitized data for the mine and urban area, and (3) land use/cover and slope maps based on Landsat Operation Land Imagery (OLI) and
Digital Elevation Model (DEM), respectively. The mine and urban area were digitized based on Google Earth’s high-resolution images and the digitized maps were then converted to shape file using ArcGIS software. Four different scenes of Landsat OLI for 2019 were downloaded from the United States Geological Survey (USGS) website (http://glovis.usgs.gov/) to cover the whole study area. The images were downloaded from June 2019 because this month provided cloud-free data for the analysis. The 11 bands obtained from each image were stacked to produce a composite image and later converted to IMG for analysis. The images were then mosaicked and a shapefile of the study area was overlaid as the area of interest (AOI) and a subset was obtained. ERDAS IMAGINE 15 (Hexagon Geospatial, Stockholm Sweden) and ArcGIS 10.5 (ESRI, Redland California) were used for image processing. Land use and cover map was derived from the classification of Landsat OLI images as indicated in Section 2.4.

2.4. Data processing

2.4.1. Suitability criteria data
Supervised classification was used to extract the land use and cover of the study area based on field survey, Google Earth images and visual interpretation technique. The dataset was trained using a specific land use class’s pixel colour tone. Each training site was created by drawing polygons. To train a single land use class, 15 polygons were drawn. This procedure was repeated for all the five land use classes and saved as a signature file using the signature editor of ERDAS software. This signature file was then used during the supervised classification stage. Supervised maximum likelihood classification technique was employed to generate five land use/cover classes: (1) dense forest, (2) medium forest, (3) open forest, (4) agriculture, and (5) settlements. For accuracy assessment, SAL (2020) recommends a minimum of 250 points for a proper accuracy assessment. Stratified random sampling was made and 300 points were generated which produce an overall accuracy of 85.67%. The Slope data was extracted from Digital Elevation Models (DEM) for the study area and utilized in analysis. The roads, rivers and wetlands shapefiles were extracted according to the study area. Buffers were generated and categorized into different classes (Figure 2). The descriptions of the different buffers are illustrated in Table 4.

2.4.2. Restriction data
Urban area and mine area were digitized based on expert interpretation of Google Earth images and knowledge of the study area. The kmz files were then converted into shapefiles using ArcGIS software and a buffer zone of 3 km was created around the urban area and the mine area to exclude these areas from primary conservation area (Figure 3).

| Criteria | Data type | Source | References |
|----------|-----------|--------|------------|
| Landsat OLI | Raster | https://earthexplorer.usgs.gov/ | Phiri and Morgenroth (2017), Goparaju, Ahmad, and Sinha (2017), Zhang et al. (2017) |
| Slope | Raster | https://earthexplorer.usgs.gov/ | Imam and Tesfamichael (2013), Goparaju, Ahmad, and Sinha (2017), Zhang et al. (2017) |
| Wetlands | Vector | https://www2.cifor.org/global-wetlands/ | Merken et al. (2015) |
| Rivers | Vector | http://geonode.rcmrd.org/layers/servir%3Azambia_rivers | Zhang et al. (2017), Ahmad, Goparaju, and Qayum (2018), Vaissi and Sharifi (2019) |
| Roads | Vector | https://geonode.wfp.org/layers/geonode:zmb_trs_roads_osm | Goparaju, Ahmad, and Sinha (2017), Zhang et al. 2017, Ahmad, Goparaju, and Qayum (2018), Vaissi and Sharifi (2019) |

2.5. Multi-criteria decision analysis model
A MCDA model was applied to determine the habitat suitability of the study area. Five factors based on literature and expert knowledge on the ground (Goparaju, Ahmad, and Sinha 2017; Ahmad, Goparaju, and Qayum 2018) were identified and used for suitability analysis. The criteria are as follows: (1) land use/cover, (2) wetlands, (3) rivers, (4) slope, and (5) roads. Two restriction factors, urban area and mine area, were also identified and used in the model that constitutes the main disturbance and danger for wildlife habitat. The data collected was then input in ArcMap 10.5 (Esri, Redland, California) software into different layers. To calculate the suitability, we multiplied the product of the suitability by that of the restriction criteria using Equation 1:

\[ S = \prod_{j=1}^{m} w_i C_l \prod_{j=1}^{m} r_j \]  

(Equation 1)

where
\[ S = \text{Forest suitability} \]
\[ w_i = \text{Weight of the criteria} \]
\[ C_l = \text{Criteria for Suitability} \]
\[ r_j = \text{Restriction} \]
\[ n, m = \text{Number of suitability criteria and restrictions, respectively} \]
Figure 2. Various thematic layers used for suitability analysis A) Land use/cover, B) wetlands and buffers, C) Rivers and buffers, D) Slope, E) Roads and buffers.

Figure 3. Restricted zone around A) mine area and B) urban area.
The five criteria are standardized using the Reclassify Tool in ArcMap because they are measured in different scales. Each criterion is weighted ($W_i$) and applied to Equation 1. AHP (Saaty 1980, 1990) applied by Ako, Rafea, and Zeren (2019) is then used to find the weights ($W_i$) of the different criteria. Each of the five criteria are then evaluated using paired comparisons. A pairwise comparison is a process where criteria are compared in pairs to determine which criteria is preferred at the detriment of the other (Ahmad, Goparaju, and Qayum 2018).

### 2.5.1. The suitability criteria’s in the analytical hierarchy process

The five criteria for analysis are described:

(i) **Land use/cover:** Forest is home to a wide range of wildlife species and is one of the most diverse land cover in the landscape. Anthropogenic activities change the structure and composition of plants within this landscape. These disturbances not only affect the forest ecosystem but also affect wildlife and their habitat (Grodsky, Moorman, and Russel 2016). Agriculture and human settlements also constitute a disturbance factor that leads to habitat fragmentation and land cover change (Kayet and Pathak 2015). Communities living near or within forests usually clear forests for agriculture and settlements, resulting in loss of some tree species, forest cover and wildlife habitat (Ahmad, Goparaju, and Qayum 2018).

(ii) **Wetlands:** Wetlands are among the most vital ecosystems with a rich biodiversity and they provide habitat to a variety of species (Zedler and Kercher 2005; Gray et al. 2013). Freshwater wetlands occupy about 8% of the surface of the earth and provide habitat to about 40% of the earth’s fauna and flora species (Lehner and Döll 2004). Wetlands provide several ecosystem services and a variety of fauna and flora species depend on the ecosystems of the wetlands for their life cycle (Mitsch and Gosselink 2000; Meng et al. 2017). Despite the ecosystems services and ecological value the wetlands provide, they are being degraded as a result of anthropogenic activities, such as hydrological alterations, land reclamation and over-exploitation (Horvath et al. 2017).

(iii) **Rivers:** Rivers constitute important habitat for aquatic species that are mainly unseen and not familiar to most people because they are hidden below the water surface. Most aquatic species like amphibians have both aquatic and terrestrial life stages and some breed in rivers, lakes, streams and other water bodies (Schofield et al. 2018) Just like larvae and eggs, they spend most of their time in these water bodies (Dijkstra, Monaghan, and Pauls 2014). The health of the environment near rivers has a direct impact on the water quality and life (Withanachchi et al. 2018).

(iv) **Slope:** The topography of a habitat influences its vegetation cover type, its vulnerability or resistance to flooding and extinction. Steep slope can have an impact on vegetation cover and growth through the acceleration of surface runoff and soil erosion (Nadal-Romero et al. 2014).

(v) **Roads:** Access to PAs is made easy by the presence of roads where human activities, such as grazing, charcoal production, poaching and tree cutting are prominently practiced (Ahmad, Goparaju, and Qayum 2018). Roads through and near PAs contribute to lowering wildlife habitat quality through elevated poaching, air and noise pollution, and vehicular-wildlife collisions (Goparaju, Ahmad, and Sinha 2017; Ahmad, Goparaju, and Qayum 2018).

### 2.5.2. The suitability criteria in the GIS

The suitability map in Solwezi district was obtained using weighted overlay technique and by integrating the different factors shown in Equation 2.

\[
W_i = \sum_{i=1}^{n} \left( [P_{LUC} \times W_{LUC}] + (P_{W} \times W_{W}) + (P_{R} \times W_{R}) + (P_{S} \times W_{S}) + (P_{Rd} \times W_{Rd}) \right)
\]

(Equation 2)

where $P_{LUC}$ is the land use/cover map, $P_W$ is the wetlands buffers map, $P_R$ is rivers buffers map, $P_S$ is the slope map and $P_{Rd}$ is roads buffers map. The $W_{LUC}$, $W_{W}$, $W_{R}$, $W_{S}$ and $W_{Rd}$ are the weightage values of each thematic layer that were used in the study area. Wetlands, rivers and roads buffers (vectors) were first rasterized before performing map algebra, combining the different layers for suitability analysis. The weight of the different criteria were obtained following the pairwise comparison (Tables 2 and 3). Pairwise comparison consists of comparing two entities together in order to decide which of the two is preferred (Ahmad, Goparaju, and Qayum 2018). These entities were selected for this study based on literature (Goparaju, Ahmad, and Sinha 2017; Ahmad, Goparaju, and Qayum 2018), expert knowledge and through consultation with local communities. Several researchers have previously applied this method for suitability analysis of various themes (Sarkar, Ghosh, and Banik 2014; Ahmad, Goparaju, and Qayum 2018; Ako, Rafea, and Zeren 2019). Thus, each
criterion was chosen based on the literature, expert knowledge and consultations with local communities and was assigned weight based on their impacts on forest in the area and through literature review (Goparaju, Ahmad, and Sinha 2017; Ahmad, Goparaju, and Qayum 2018). Table 4 shows the weighting for the different layers used for wildlife habitat suitability mapping.

The values 1 to 9 indicate the level of important for the classes in the criterial used (Saaty 1980, 2000). 1 for equal and 9 for extreme.

2.5.3. The restrictions
Areas with high human impacts, such as urban area and mine area were excluded and not considered in the selection of potential PAs using the buffer zones as shown in Figure 3. The two restriction criteria for analysis are described:

(a) **Mine area**: Mine represents a major threat to biodiversity, whereby it reduces its quality (Cristescu, Stenhouse, and Boyce 2016). The area where the mine activities take place should be separated from the PA. Wildlife habitat, 3000 metres within the vicinity of the mine area, is of low quality (Ahmad, Goparaju, and Qayum 2018).

(b) **Urban area**: Urban area represents a big source of disturbance and is highly unsuitable for biodiversity conservation (Patten and Burger 2018).

2.6. Structure of the GIS model
The suitability and restriction models were created to classify the suitability in the study area. Figure 4 illustrates the methodology used in this study. For the Suitability Model, the weights of the criteria from the AHP were applied in the Weighted Overlay Tool in ArcGIS following \( \sum_{i=1}^{m} w_i C_i \) to generate the suitability map. The restricted areas were calculated using the restriction model \( \prod_{j=1}^{m} r_j \). The final suitability model was obtained by the product of the Suitability Model and the Restriction Model.

### 3. Results
The suitability model and the restriction model were run and the maps obtained from these two models were run in order to produce the final suitability map. Maps of different protected areas were extracted in order to display the state of protected forest areas. All the protected forest areas in Solwezi district have marks of anthropogenic disturbance. Mbonge forest is completely restricted because it falls under the area where mining activities are carried out (Figure 5). As a result of the expansion of the Solwezi town, Solwezi forest areas have also experienced serious disturbances. Mutanda forest appears to be the least disturbed protected forest area in the district (Figure 5). Table 5 provides the summary of the different suitability areas for the 5 protected forest areas present in Solwezi district.

The final forest area suitability map of the study area with five different levels of suitability is illustrated in Figure 6. Table 6 provides the values of the final forest area suitability map that is a product of the suitability and restriction map. The results show that 30.4% of the total area is extremely suitable for conservation, 21.2% is highly suitable, and 14.9% is moderately suitable. The same area has 18.1% of area that is low suitable for conservation and 15.4% of the area is restricted from

### Table 2. Pairwise comparison matrix.

| Criteria | Land use/cover | Wetlands buffers | Rivers buffers | Slope | Roads buffers |
|----------|----------------|-----------------|---------------|-------|---------------|
| Land use/cover | 1 | 2 | 2 | 4 | 4 |
| Wetlands buffers | 1/2 | 1 | 2 | 3 | 4 |
| Rivers buffers | 1/2 | 1 | 1 | 3 | 4 |
| Slope | 1/4 | 1/3 | 1/3 | 1 | 3 |
| Roads buffers | 1/4 | 1/4 | 1/4 | 1/3 | 1 |
| Sum | 2.5 | 4.5833 | 5.5833 | 11.3333 | 16 |

### Table 3. Normalized Pairwise Comparison Matrix.

| Criteria | Land use/cover | Wetlands buffers | Rivers buffers | Slope | Roads buffers | Priority vector | Weight |
|----------|----------------|-----------------|---------------|-------|---------------|-----------------|--------|
| Land use/cover | 0.4 | 0.4364 | 0.4364 | 0.3529 | 0.25 | 0.375 | 38 |
| Wetlands buffers | 0.2 | 0.2182 | 0.2182 | 0.2647 | 0.25 | 0.23 | 23 |
| Rivers buffers | 0.2 | 0.2182 | 0.2182 | 0.2647 | 0.25 | 0.23 | 23 |
| Slope | 0.1 | 0.0727 | 0.0727 | 0.0882 | 0.1875 | 0.104 | 10 |
| Roads buffers | 0.1 | 0.0545 | 0.0545 | 0.0294 | 0.0625 | 0.06 | 6 |
| Consistency = 4% | principal Eigen value = 5.193 | | | | | | |

### Table 4.

| Criteria | Normalized Pairwise Comparison Matrix |
|----------|---------------------------------------|
| Land use/cover | 0.4 | 0.4364 | 0.4364 | 0.3529 | 0.25 | 0.375 | 38 |
| Wetlands buffers | 0.2 | 0.2182 | 0.2182 | 0.2647 | 0.25 | 0.23 | 23 |
| Rivers buffers | 0.2 | 0.2182 | 0.2182 | 0.2647 | 0.25 | 0.23 | 23 |
| Slope | 0.1 | 0.0727 | 0.0727 | 0.0882 | 0.1875 | 0.104 | 10 |
| Roads buffers | 0.1 | 0.0545 | 0.0545 | 0.0294 | 0.0625 | 0.06 | 6 |
| Consistency = 4% | principal Eigen value = 5.193 | | | | | | |
conservation practice. The restricted area represents a buffer zone from the mine and urban centre which are areas where conservation may not effectively take place because of very high disturbance.

The results also portray a fragmentation of all the existing protected forest areas but with different degrees of disturbance. All the protected forest areas in Solwezi district have marks of anthropogenic disturbances. Mbonge protected forest area was de-gazetted by the Zambian government in the early 2000s to pave a way for establishment of the mining site. Mulenga protected forest area has the highest patches of lowly suitable areas within the district with some few patches of moderately suitable, highly suitable and extremely suitable areas. Chimbe protected forest area also contains a high number of lowly suitable patches, few patches of moderately suitable and more patches of highly and extremely suitable areas compared to Mulenga protected forest area. Part of the Solwezi protected forest area falls under the restricted area which is unsuitable for conservation because of its proximity to the urban area of Solwezi district. The other part of Solwezi forest area has bigger areas of extremely and highly suitable areas with low areas of moderately and lowly suitable areas. With low level of encroachment and anthropogenic activities, Mutanda protected forest area appears to be less affected by people.

4. Discussion

This study applied a combined GIS-MCDA approach to assess the state of PAs in a mining and human-dominated landscape. GIS-MCDA is the perfect combination of spatial information and decision-making processes, and it is used to evaluate monitoring priorities and select a suitable area in which monitoring sites can be established (Wang and Du 2016). GIS was used to assess the state of PAs and classify the study area into different levels of suitability for forest conservation. A set of suitability criteria were selected based on literature and expert knowledge and process using the AHP. Many studies used the AHP methodology to determine the forest suitability (Farashi, Naderi, and Parvian 2016; Ahmad, Goparaju, and Qayum 2018; Bakirman and Gumusay 2020). The AHP was found by these studies to be an easy and an appropriate tool to estimate the weights of the different criteria. The restriction criteria were further used in order to supplement the model by excluding areas that can constitute a high ecological risk because of their proximity.

The results obtained from this study show a clear impact of human activities on the protected forest areas in the study area. Based on the model, Mbonge (a de-gazetted forest area, currently undergoing mass land conversion from forest to other land-uses, such as agriculture and human settlements) has been extensively degraded. Solwezi protected forest area as a result of its proximity to the urban area has portion that have been encroached by anthropogenic activities though part of this protected area (PA) still has patches that are highly suitable for conservation. Mulenga and Chimbe protected forest areas also have a lower suitability levels because of their proximity to the mine area that attract a lot of other anthropogenic activities. The high level of encroachment of these PAs could also be attributed to the displacement of local communities from the mine area. Communities living around the Kansanshi mine in Solwezi district were displaced as a result of mining activities and for the construction tailings dam for the mine (Van Alstine et al. 2011). Anthropogenic activities, such as mining, urban development and agriculture lead to a drastically reduction of forest, which result in the fragmentation and destruction of wildlife habitat to an extent that the survival of wildlife species is threatened (Imam and Tesfamichael 2013; Williams et al. 2016; Taylor-Brown et al. 2019; Rastandeh, Jarchow, and Carnes 2021).

Table 4. Weightage for thematic layers used for forest suitability mapping.

| Weights of Thematic layer | Weight (%) | Description | Ranking | Intensity |
|---------------------------|------------|-------------|---------|-----------|
| Land use/cover            | 38         | Dense forest| 9       | Very high |
|                           |            | Medium forest| 7       | High      |
|                           |            | Open forest  | 5       | Medium    |
|                           |            | built-up     | 2       | Low       |
|                           |            | Agriculture  | 2       | Low       |
|                           |            | 1 km         | 6       | Very high |
| Wetlands buffers weightage| 23         | 1.5 km       | 5       | High      |
|                           |            | 2 km         | 4       | Medium    |
|                           |            | 2.5 km       | 3       | Low       |
|                           |            | > 2.5 km     | 2       | Very low  |
| Rivers buffers weightage  | 23         | 1 km         | 6       | Very high |
|                           |            | 1.5 km       | 5       | High      |
|                           |            | 2 km         | 4       | Medium    |
|                           |            | 2.5 km       | 3       | Low       |
|                           |            | > 2.5 km     | 2       | Very low  |
| Slope                     | 10         | 0% - 5%      | 6       | Very high |
|                           |            | 5% - 10%     | 5       | High      |
|                           |            | 10% - 16%    | 4       | Medium    |
|                           |            | 16% - 36%    | 3       | Low       |
|                           |            | > 36%        | 2       | Very low  |
| Roads buffers             | 6          | 1 km         | 2       | Low       |
|                           |            | 2 km         | 3       | Medium    |
|                           |            | 3 km         | 4       | High      |
|                           |            | > 3 km       | 5       | Very high |
GIS-MCDA approach in spatial analysis involves the combination, processing and transformation of data into a decision. In the process, the spatial data are manipulated and used according to the preferences of the decision-maker (Drobne and Lisec 2009). MCDA was found as a very important tool in the study of environment-related problems; for example, assessing the state of existing PAs and identifying new sites for wildlife habitat suitability and conservation. The tool can provide simultaneous information on sites of other possible areas that should be protected or on the value of criterion using both GIS-MCDA methods (Malczewski 2010). In the present study, a set of data have been combined to generate suitable areas for forest conservation in a highly disturbed area. The GIS-MCDA method used in this study can be an important tool that can provide decision support to policy makers, and help practitioners attain efficiency in the spatial management and monitoring of protected forest areas by providing alternatives to a series of evaluation criteria. GIS-MCDA remains a tool of choice to specialists as it allows an integration of several spatial data for spatial analysis to generate novel knowledge (Wang et al. 2008; Ako, Rafea, and Zeren 2019; Vaissi and Sharifi 2019).

This study has shown that the forest conservation planning requires spatially accurate information about the potential distribution of trees and the categorization of forest suitability is a good start as a generalization tool.
The level of suitability may need to be tested by practitioners in order to confirm the different levels of suitability generated by the model. The output map could be used as baseline information by forest department and other agencies in charge of forest conservation to classify forest suitability in the field using this scheme and help proactive forest conservation planning. While GIS-MCDA allows integration of expert knowledge, it helps in promoting effective conservation planning (Imam and Tesfamichael 2013). It enables managers to develop new choices based on a set of spatial data-related criteria (Chen 2014). In-depth studies on the suitable areas generated from the model may be required and conducted by conservation expert. The GIS-MCDA is a cost-effective method that may provide baseline information in the initial stage for the assessment of the quality of the existing PAs and in the selection of new sites for conservation. The flexibility of the model applied in this study can enable experts and other stakeholders to rapidly integrate new criteria or ideas when required (Zhang et al. 2013). The approach used in this study to assess the state of PAs and identify new areas for conservation can be easily adapted to other areas of conservation.

Some studies have revealed the importance of GIS-MCDA as a tool to prioritize decisions in the field of conservation science (Zhang et al. 2013; Farashi, Naderi, and Parvian 2016; Vaissi and Sharifi, 2019). Farashi, Naderi, and Parvian (2016) applied a combined participatory method with a GIS-MCDA approach to design a zoning pattern for a PA in Iran. Zhang et al. (2013) applied a methodology that incorporates a participatory approach with GIS using a MCDA approach to guide a zoning scheme of a national park in China. Vaissi and Sharifi (2019) also used a GIS-MCDA method to select PAs for protection of a vulnerable and endemic species in southern Iran.

The results from this study are important for the conservation of forest resources in Solwezi district. Areas that are currently designed as PAs do not fit to the current mining and urban expansion of the district. As we can observe in Figure 6, most areas considered safe and protected in the old zoning plan of the district are different from the proposed areas generated by the GIS-MCDA.
applied in this study. This result was expected because like many Sub-Saharan African countries, there appear to be lack of coordination between forest conservation planning and development planning in Zambia.

There is thus a critical need for forest conservation planning to be integrated with development planning in order to avoid potential conflicts and ensure long-term sustainable development (Salafsky 2011; Watson et al. 2015; Kabir et al. 2020). As a spatial insurance, the diversity of forest structure and composition must be maintained at landscape and regional scales to provide habitat for a diverse range of specialist forest species (Brockerhof et al. 2017). Forests provide habitat for a diverse range of taxa and trophic levels, which has a positive impact on forest ecosystem functioning through a variety of mechanisms (Lindenmayer 2017). In Zambia, a number of development projects for infrastructures, roads, agriculture, and other projects that have been implemented or are yet to be implemented can often conflict with the management goals of PAs like forest reserves and Game Management Areas (RDA 2013). To ensure that such projects do not interfere with one another, Watson et al. (2015) suggest that a better coordination and planning among governmental institutions and agencies should be a topmost priority. Simwanda et al. (2021) also mentioned that environmental sustainability can only be achieved if it is linked to social and economic sustainability.

To reduce the extinction of species, there is also a need for increased public and political support for sustainable forest management. Using basic community-level metrics (e.g. species richness, abundance, and species

Figure 6. Final forest area suitability map.
Table 6. Area under different categories of forest suitability.

| Area(he)       | Restricted area | Lowly suitable | Moderately suitable | Highly suitable | Extremely suitable |
|----------------|-----------------|-----------------|---------------------|-----------------|--------------------|
| Percentage (%) | 15.4%           | 18.1%           | 14.9%               | 21.2%           | 30.4%              |

composition), the effects of large-scale forest harvesting, thinning, and replanting with exotic species on habitat provisioning for well-known groups of mammals, birds, and plants have been relatively well investigated. However, the effects of forest management and mitigation measures on less charismatic groups like invertebrates and fungi, and for more complex community interactions and ecosystem functions, as well as longer-term impacts like climate change, are largely unknown. This is especially true for the biota associated with forest canopies, as well as the flora and fauna of tropical forests, where the effects of forest fragmentation and modern forest practices are largely unknown, despite the high conservation value of these forests and their important role in providing ecosystem services (Brockerhof et al. 2017).

There has been an increase in the use of GIS and remotely sensed data together with simple overlaying techniques in Zambia for forest conservation monitoring and planning over the past years (Kasaro, Phiri, and Nyambe 2019; Lungu, Knight, and Adam 2019; Musole, Ololade, and Sokolic 2019). However, when combined with MCDA, forest and environmental management activities in Zambia may be more accurate, fast and cost-effective. Moreover, this study aims at demonstrating to natural resources practitioners the benefits of combining MCDA with GIS in the decision-making process. Areas which are highly suitable for conservation have been identified and hence, ideal conservation programmes (e.g. reforestation, restocking) can be implemented there. In addition, effective monitoring programmes can be applied in this area because locations that need serious attention have been identified. Thus, the findings from this research will help decision makers to make better choices on the ideal programmes.

With the bid to reduce forest degradation and deforestation in our study area, based on our results, and in order to ensure effective protection of the protected forest areas in Solwezi district and, at the same time, to safeguard the livelihood of the local people, local communities should be educated and sensitized about the issues around deforestation and the need to protect forests. They should be educated on issues regarding natural values and resources in the conservation of forests because it is important that modern scientific knowledge is combined with indigenous knowledge in managing the forests. There is also need to reduce household dependency on charcoal through coordinated policies providing alternative income opportunities for entire charcoal value chain, provision of affordable alternative sources of energy for rural peri-urban households and efficient and sustainable production and use of wood fuel. The government should involve local communities in forest management. The government will develop and strengthen the local people’s capacities by involving them, allowing them to become more responsible in their utilization of the forest. There is a need to change policy makers’, forestry officials’, and local people’s perceptions and attitudes towards forest resources by educating them about the intrinsic and inherent values that diverse natural non-life forms and life-forms have, as opposed to the utilitarian values that are currently dominant.

The results of our study should, however, be interpreted within the limitation of this research. First, we used five suitability and two restriction criteria, but increasing the number of factors such as population density, climate, and forest fires could improve the results of this study. Secondly, we used different input data, though from approved sources, and we had no control over input data quality. For example, although our classification results were high, some errors of omission and commission could be expected. As an avenue for future studies, we recommend using more ecological, environmental and socio-economic criteria for building the model, as the flexibility of the GIS-MCDA allows the integration of new criteria into the model.

5. Conclusions

The GIS-MCDA is a cost-effective approach used in this study has demonstrated a great potential in assessing the state of protected forest areas. The rapid urbanization, urban sprawl and human population boom as a result of mining activities in the district have fragmented forest areas at a large scale. This cost-effective and time saving method can be utilized by researchers, policy makers, planners and managers in charge of biodiversity conservation. Due to the flexibility of the model, new datasets can be integrated into GIS-MCDA model. We recommend a monitoring of the PAs using geospatial techniques to identify disturbed and degraded areas, and monitor the PA health. Through effective
monitoring of protected forest areas, conservation policies may be supported by science-based evidence.

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