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Multi-Criteria GIS modelling for optimal alignment of roadway by-passes in the Tlokweng Planning Area, Botswana

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Abstract

To find the optimal by-pass road alignment in the Tlokweng Planning Area in Botswana, a multi-criteria spatial-based model is developed using the GIS-MCE approach. In respect to the environmental impact assessment (EIA) approach, in this research a set of criteria is classified under 3 themes – economic, environmental and social. To determine the criterion and theme weights and perform their aggregation, the Analytical Hierarchy Process (AHP) and Weighted Sum (WS) are utilised. The least-cost path analysis is used to produce road alignments. The entire model is developed using ModeBuilder in the ArcGIS 10.5 environment. Depending on the theme's preference, 4 road alignments are produced: economic, environmental, social and equal. Comparing GIS-produced alignments and the planned route proposed in the "Tlokweng Development Plan 2025" is carried out by applying an independent validation matrix using the DEFINTE software package.

The investigation into the robustness of the model is completed by examining the model output to identify criteria sensitive to weight changes. For this purpose, One-At-a-Time (OAT) sensitivity analysis and the statistical test for zero proportion are used. Sensitivity analysis results for criteria identified as sensitive are also presented spatially. To carry out the sensitivity analysis, a standalone Python script has been created which communicates with ArcGIS 10.5 through the ArcPy module.

This study has successfully investigated, developed and applied the MCE method for optimal planning of highway and road alignments together with a sensitivity analysis for the MCE method. The results show that the social alignment is the best of the 4 road alignments – economic, environmental, social and equal. The results further confirm that the planned alignment, not produced by applying the multi-criteria approach, substantially differs from the 4 mentioned routes produced in GIS. The results of the sensitivity analysis and statistical test for zero proportion reveal 6 criteria as sensitive. The criterion referring to land use/land cover displays the greatest difference in the results – the model becomes sensitive at -5% of this criterion weight change.

Further research is recommended to increase the robustness of the model. Some recommendations are further analyses regarding the assignment of criteria weights, standardisation of criteria and applying a "global" sensitivity approach in which more than one criterion weight is changed at a time.

Keywords: Multi-criteria analysis; AHP; Least-cost path; Dijkstra's algorithm; DEFINITE, Sensitivity Analysis; Python, ArcPy

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Holding a full-time job as a traffic engineer concurrent to writing this thesis proved quite challenging. Many evenings, weekends and holidays were needed to complete it. It was not only my passion for GIS that kept me going and not giving it up but also two very special girls. My biggest thanks go to my wife Dijana, who encouraged me throughout and displayed patience and understanding at having to spend many evenings alone. And, to our little baby Alissa who began her life journey around at the time I started this thesis and has been my biggest source of strength and inspiration ever since ☺.

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1 Introduction

A transportation network is imperative both to the development and continued economic sustainability of communities. However, roads and highways must be well planned to prevent economic, ecological and social risks. Defining well-planned and optimal road alignment represents a challenge as many criteria need to be considered (Singh & Singh, 2017; Yakar & Celik, 2014; Saha et al., 2005; Belka, 2005). Several approaches have been used so far.

One of the most important criteria determining road alignment in many countries is slope (Yakar & Celik, 2014). The usual practice involves using large-scale topographical maps on which line segments are placed in respect to the allowable slope of terrain. After producing several alternatives, detailed analysis is conducted on other aspects of terrain suitability. Further, environmental and economic aspects are estimated and the final road alignment is then chosen. This approach has many disadvantages as economic, environmental and social criteria are not jointly considered and thus the obtained road alignment cannot be considered optimal.

On the other hand, in some cases the planning team pays greater attention to economic and social criteria. The environmental impact of the planned infrastructures is only considered after the road alternatives have been developed. This means that social and economic criteria are optimised, but environmental ones are not (Belka, 2005).

Carrying out an Environmental Impact Assessment (EIA) in large-scale infrastructure projects represents a more advanced approach to road planning. Many countries point to the importance of including EIA throughout the process from the planning stage to implementation. This brings many benefits as it takes economic, environmental and social criteria into consideration right from the start (Swedish Transport Administration, 2011; Gonzalez & Enriquez-de-Salamanca, 2018).

Identifying optimal road alignment represents a spatial problem involving many – usually conflicting – criteria. Spatial-based Multi-Criteria Evaluation (MCE) can be applied to tackle this. It involves combining and transforming geographic data into a final output (Malczewski, 1999).

MCE and GIS have been extensively applied to many problems in different fields since 1990 (Malczewski, 2006). One application is transportation where they have been used to solve vehicle-routing problems. However, to date few papers have dealt with the problems of MCE and GIS application in determining road corridors. This thesis contributes to defining a methodology in highway planning practice.

This work will propose a spatial-based integrated approach that considers economic, environmental and social criteria together in the early stages of large-scale projects, in this case a by-pass road alignment. For each of the 3 mentioned groups, a set of criteria will be defined then combined through multi-criteria evaluation (MCE) in a spatial environment using a geographic information system (GIS). GIS is capable of performing spatial analyses and thus suitable for analysing these criteria. This way many alternatives can be produced and compared. A case study applies this approach to a road by-pass alignment in the Tlokweng Planning Area, Botswana.

1.1 Aim of the thesis

This thesis aims to *develop and implement the spatial-based, MCE approach which enables optimal planning of highway and road systems.*

This work will address the following test questions that will contribute to the above-mentioned overall purpose:

- *Which by-pass alignments are preferable in respect to economic, environmental and social characteristics of the study area?*
- *How do the results of the proposed MCE approach compare to the by-pass alignments proposed by a plan? and*
- *Which criteria are most sensitive to weight changes by conducting sensitivity analysis?*

1.2 Study area

The study area of this research is the Tlokweng Planning Area – TPA in Botswana (see Figure 1). The boundaries of the Planning Area include Tlokweng village together with its immediate hinterland[1]. The total area size is 28 389 ha, 3 356 ha of which comprises the built-up area of Tlokweng village. According to the 2011census, the Tlokweng Planning Area has a population of 365 000, which makes Tlokweng village the 13th-largest settlement in Botswana (GIS Plan, 2018).

To the west, Tlokweng shares a border with the nation's capital city – Gaborone. Its proximity to Gaborone makes it a peri-urban settlement with both, urban and rural characteristics. It borders to the south with the Republic of South Africa and to the east with the Kgatleng District.

Surveys reveal that national road A12 (Tlokweng – Zeerust road) suffers from serious traffic congestion, especially the section between the Tlokweng urban area and Gaborone. It has been acknowledged that through traffic from the Tlokweng border, particularly heavy trucks, places pressure on A12 making this traffic congestion during the peak hours (GIS Plan, 2018).

To improve traffic flow on road A12 and reduce congestion, two roads – northern and southern by-passes – are proposed in the Tlokweng Development Plan. The main intention is to divert heavy articulated trucks carrying goods from South Africa to Francistown, Maun, Kasane, Zambia and Namibia, from passing through Tlokweng village (GIS Plan, 2018).

The Tlokweng study area and the two proposed by-pass roads are shown in Figure 1.

To define by-pass alignments, no multi-criteria analysis was utilised. However, different environmental criteria were used together with the Strategic Environmental Assessment to produce the proposed by-pass road alignments. The main characteristic of this process was high public participation from the local residents living within the Tlokweng Planning Area.

[1] These are Traquair 10-KO, Athol Home 11-KO and Kentholme 13-KO and Notwane 14-KO (see Figure 1)

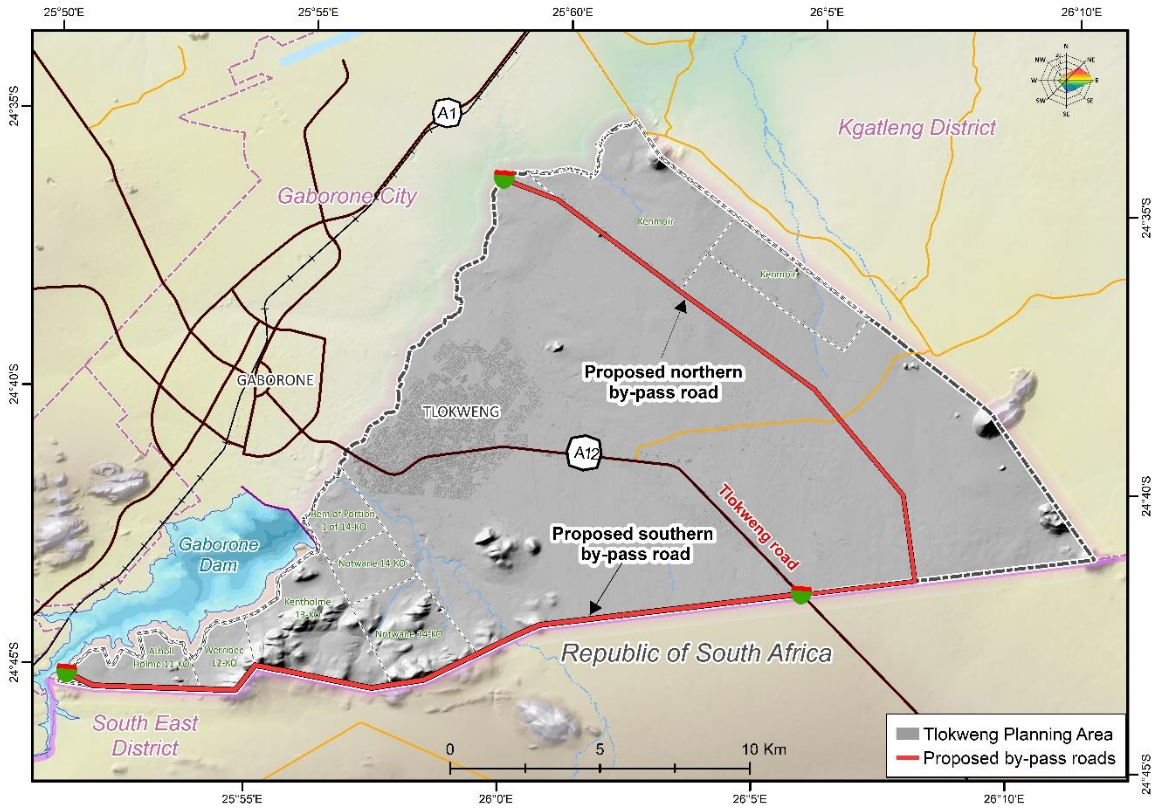

Figure 1.the Tlokweng Planning Area – TPA and proposed by-pass roads (GIS Plan, 2016)

1.3 Thesis outline

This thesis is organised into 7 chapters.

Chapter 1 is the introduction stating a framework of the problem, the aim of the thesis and the test questions. It also gives a short description of the study area in the state of Botswana – the Tlokweng Planning Area. Chapter 2 is a literature review providing an overview of selected research papers in which a combination of GIS and different MCE techniques has been applied. This section shows how MCE-GIS has been applied in different fields and presents the MCE techniques important for this thesis. The second section shows research carried out in respect to the stated problem – application of MCE-GIS in the road-planning process. Chapter 3 offers a theoretical background which aims at presenting the road planning practice utilised in the state of Botswana. Secondly, it gives an overview of the MCE process. Finally, it presents the GIS algorithms that help to produce road alignments. Chapter 4 is data collection describing all geospatial data used to perform the analysis. Chapter 5 presents the thesis methodology. Chapter 6 gives the results for by-pass road alignments produced by GIS as well as the validation of the model applied in the case study. Finally, it presents the results of the One-At-a-Time sensitivity analysis. Chapter 7 offers the conclusion based on the defined test questions. The final chapter provides a set of recommendations for future work.

2 Literature review

Multi-criteria evaluation (MCE) is a sub-discipline of Operation Research (OR) dealing with decision problems by evaluating multiple criteria that are usually in conflict with each other (Triantaphyllou et al., 1998; Fernando et al., 2011). MCE is a valuable tool that can be used to solve many complex problems. It is mainly applicable to finding a solution, for example, an optimal/best alternative, among many. There are many MCE techniques, all of which have both advantages and disadvantages. Different methods within MCE will give different results (Heywood et al., 1995).

GIS-based MCE has been applied in many fields such as environmental planning and management, transportation planning, urban and regional planning, waste management, hydrology and water resources, agriculture and forestry, geology and natural hazards, and real estate and industrial facility management. There was exponential growth in published GIS-based MCE papers from 1994 to 2004 (Malczewski, 2006).

Table 1 shows a selection of publications focusing on GIS-based MCE. It gives the source, the MCE method used and its application. Generally, GIS-MCE is used to solve site evaluation problems, such as location of solar and wind farms, landfills, solving problems in urban and regional planning. There are, however, several published research papers that relate to GIS-based MCE in highway or road planning (marked orange).

The idea of introducing the environmental prospective at the beginning of the road planning process was stated by Rapaport in 1999 (Rapaport & Snickars, 1999). This was important because Rapaport's research pointed out that in order to find the optimal road alignment, the environmental criteria should be considered at the same time as the others usually used in the road planning process, such as economic and technical criteria. Since his research, however, the introduction of EIA within the GIS-based MCE approach when defining road alignment has been mostly underdeveloped and considered in few papers (Belka, 2005; Hala & Hassan, 2013). Today, EIA is a highly recommended approach for road infrastructure projects and thus there is a distinct need to include it within the GIS-MCE approach. Thus, it may have been crucial to tackle the problem of defining road alignments by clearly classifying spatial criteria in accordance with the EIA approach. This will allow the production of several road alignments that could be compared and the most viable chosen.

Regarding the used MCE approach in papers dealing with the road planning process (Table 1), the description of MCE elements appears somewhat vague (Singh & Singh, 2017; Saha et al., 2005; Sadek et al., 1999; Rapaport & Snickars, 1999). On the other hand, few papers clearly state the used MCE-GIS approach such as the application of Weighted Sum (WS) and Saaty's Analytical Hierarchy Process (AHP) (Yakar & Celik, 2014; Hala & Hassan, 2013; Tae-Ho et al., 2008; Belka, 2005). What is common for the majority of these papers is the lack of any sensitivity analysis (SA) being conducted.

According to Malczewski sensitivity analysis should be an integral part of the MCE (Malczewski, 1999); however, SA has not been performed in most GIS-based MCE research (Malczewski, 2006; Malczewski & Rinner, 2015; Delgado & Sendra, 2004). This is a significant drawback as the robustness of developed model in different studies is not investigated and therefore remains unknown. Among the papers listed in Table 1 dealing specifically with road planning, only one features sensitivity analysis (Yakar & Celik, 2014). In this research the criteria weights are changed and then the output results investigated by looking more closely at rank changes of investigated routes. There are several drawbacks in the SA approach used in Yakar's research. Firstly, the SA was not performed on the entire model; that is the entire space within the study area. Each cell within a raster dataset represents a possible solution in developing the road alignment. Thus, using SA to check the behaviour of the cells only used in road alignment creation, could be misleading when forming conclusions about the sensitivity of the model. If no changes in the route ranking are noticeable, one can conclude that the model is stable enough and could thus be used in different studies without further checks. However, the model could be more sensitive in some parts of the study area than in others. If the points between which the road alignment should be placed are moved and used in another part of the study area, the conclusion of the SA will be different. Thus, rather than investigating the robustness of some raster data cells, the entire model sensitivity should be investigated. The second aspect not investigated in Yakar's study is spatial sensitivity. Besides quantitative SA presentation, it is useful to present sensitivity spatially within the study area. This gives the locations of sensitive areas and where more investigation is needed in order to learn more about model robustness.

In order to compare and evaluate the obtained route alignments, different approaches have been used. In most papers dealing with road alignments shown in Table 1, it is noticeable that the road-alignment selection is conducted in regard to horizontal road alignment characteristics (two-dimensional information). This has the major drawback of the road alignment selection also being highly dependent on its vertical characteristics. Thus, the third dimension needs to be introduced in the process of finding the optimal road alignment. It holds particular importance for cut and fill work which greatly affects road construction costs. This was pointed out in research by Tae-Ho and Hala, as they also considered the vertical alignment characteristics in the road alignment planning (Tae-Ho et al., 2008; Hala & Hassan, 2013).

The next aspect important to review is how GIS was used to find the optimal road alignment. This is more of the practical purpose as it is important that the model can quickly give a range of solutions. Belka used the EIA approach for grouping different criteria and different MCE techniques to define the optimal road alignment where all steps were performed manually (Belka, 2005). On the other hand, other papers do not clearly state if the automated model was developed. In order to improve the process and avoid human error when finding solutions, it is worth noting that the entire process should be automated by developing models that could be run repeatedly or by developing separate modules within a GIS environment. This approach is proposed in several papers, in which the authors developed tools that with slight adjustment could be applicable to other study areas (Tae-Ho et al., 2008; Sadek et al., 1999). This is also an important point to be considered in GIS-based MCE approaches.

Based on the above review and stated shortcomings when using a GIS-MCE approach within road planning practice, this thesis will try to shed light on the following aspects. It will first group the predominant criteria within the study area in accordance with EIA, namely economic, environmental and social criteria. Further, it will clearly present the entire GIS-based MCE approach and all important elements. The main focus will be the application of SA on the entire GIS model, from a quantitative and spatial point of view. Characteristics of vertical alignments as an important component in cut and fill work calculations will be introduced in a comparison process of GIS-produced road alignments. Finally, the entire process will be automated using tools available in the ArcGIS 10.5 environment.

Table 1. Spatial MCE publications in different fields

Source	MCE Method	Application
Singh & Singh, (2017)	No detailed information about determining criterion weights; weighted sum approach	Road-alignment planning in the city of Allahabad, India
Latinopoulos & Kechagia (2015)	Weighted linear combination and Saaty's analytical hierarchy process	Wind-farm location
Khan & Samadder (2015)	Weighted linear combination and Saaty's analytical hierarchy process	Landfill location
Tahri et al., 2015	Weighted sum overlay and Saaty's analytical hierarchy process	Solar-farm location
Kumar et al. (2015)	comparison of 4 methods: ranking, rating, pairwise comparison, and trade-off	Urban development
Abudeif et al. (2015)	Weighted linear combination and Saaty's analytical hierarchy process	Nuclear-power-plant location
Yakar & Celik, (2014)	Weighted linear combination and Saaty's analytical hierarchy process	Road-alignment planning in the Black Sea region of Turkey
Rikalovic et al. (2013)	Linear scale standardisation	Industrial-site location
Akıncı et al. (2013)	Weighted sum overlay and Saaty's analytical hierarchy process	Agricultural-land location
Uyan, (2013)	Weighted sum overlay and Saaty's analytical hierarchy process	Solar-farm location
Hala & Hassan, (2013)	Weighted sum and Saaty's analytical hierarchy process	Road-alignment planning in the Sinai Peninsula desert in Egypt
Moeinaddini et al. (2010)	Weighted linear combination and Saaty's analytical hierarchy process	Landfill location
Tae-Ho et al. (2008)	Weighted linear combination and Saaty's analytical hierarchy process	Road-alignment planning in the Pusan Metropolitan City, China
Saha et al. (2005)	No detail information	Road-alignment planning in the Himalayas region, India
Belka, (2005)	Expert opinion for criterion weights and simple additive weighted method	Road-alignment planning in Poland

Chen et al. (2001)	Weighted linear combination and Saaty's analytical hierarchy process	Developing a prescribed burning plan for bushfire prone area
Sadek et al. (1999)	No detail information	Road-alignment planning in Beirut, Lebanon
Rapaport & Snickars, (1999)	No detailed information about determining criterion weights; weighted sum approach	Road-alignment planning in Botkyrka, Sweden

3 Theoretical background

In this chapter, the road-planning practice relevant to the Republic of Botswana will be briefly presented. Secondly, the main elements included in the GIS-MCE approach will be given in more detail. Finally, the important algorithm within the GIS method, which helps to produce by-pass road alignments, is also presented in more detail.

3.1 Road-planning process in Botswana

Road-infrastructure planning represents a part of physical planning that includes town and land use planning. Road developments are an important prerequisite for other types of development. For example, the relationship between road network development and land use is well established (Ministry of Works, Transport & Communications, 2001). The land-use-road-network relationship shows what usually occurs when a road network is built or improved. When a road network is developed, the land alongside the roads becomes more accessible, which increases its value and attractiveness to developers.

For large-scale road-infrastructure projects it is common to conduct an Environmental Impact Assessment (EIA). The EIA is a tool that applies scientific knowledge to identify the environmental, social and economic impacts of a project prior to it being green-lighted (Shah et al., 2010). Thus, it encompasses 3 main aspects of human surroundings: environmental, society and economy.

In general, a road-planning process has 3 stages, illustrated in the figure below:

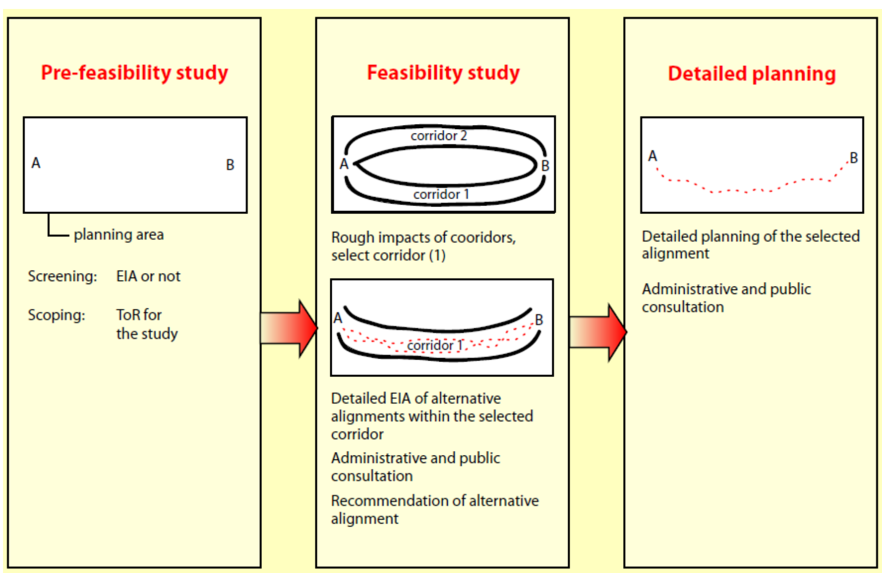

Figure 2. Overview of a road-planning process in Botswana (Ministry of Works, Transport & Communications, 2001)

The first stage is the *pre-feasibility study* which determines if a detailed EIA is necessary. This is usually related to small-scale projects that do not automatically require an EIA. Large-scale road-infrastructure projects usually skip this stage as an EIA is required for the planning process. In this stage, a certain amount of data in respect to landscape and environment needs to be collected within planning area (through research, consultation, filed inventories, etc…).

The second stage is a *feasibility study* which focuses on finding a suitable geographical location for a new road within a given landscape. The purpose is to carry out a detailed investigation of different road-alignment alternatives by taking economic, environmental and social factors into account. This involves a detailed collection of existing data within the planning area and consultation with different stakeholders and other experts. The outcome should be a chosen alignment deemed the most viable and then approved for detailed planning.

In this second stage, GIS can be an extremely helpful tool during the whole planning process. The wide capabilities of GIS are found to be useful as spatial data could be collected in a geodatabase and combined using different MCDA techniques to attain a reasonable solution. Figure 3 illustrates a simplified example of how GIS could assist in the planning process. Certain spatial criteria are defined to create vulnerability maps that help in identifying the least vulnerable areas to place an optimised road route. Utilisation of MCE within GIS and different elements of MCE are presented in the following section.

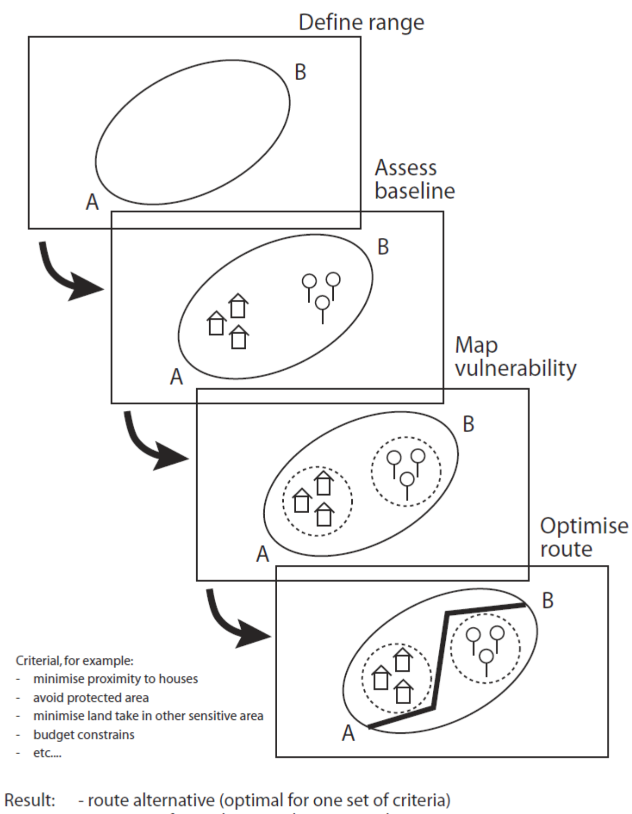

Figure 3. Combining different layers in GIS under feasibility study (Ministry of Works, Transport & Communications, 2001)

Finally, the third stage – *detailed planning* – encompasses several steps, including geometric design, pavement design, design of bridges and culverts, traffic studies, etc…

At this point it is apt to mention that this master's thesis focusses on the second stage – the *feasibility study*. The built GIS model will propose different by-pass road alignments and will not focus on detailed road geometry (vertical and horizontal curves, road profile, etc…).

3.2 Multi-Criteria Decision Analysis (MCDA) and Geographic Information Systems (GIS)

The application of MCDA techniques within a GIS environment developed over time. In the 1950s advances in computer technology and spatial science led to the development of GIS. In this stage GIS was mainly used in scientific research where it developed into a new discipline. By the 1980s several commercial GIS systems had been developed. National agencies started to see the advantages of digital mapping and began to adopt it. GIS was not just viewed as a collection of data; it was deemed useful in the planning process. In the 1990s the nature of planning changed, characterised by the increased involvement of non-experts (the public, stakeholders, non-governmental organisations, etc.) in the planning and decision-making process. During this period the introduction of MCDA in GIS received considerable attention from planners (Malczewski & Rinner, 2015; Malczewski, 2003). This integration paved the way for a decision maker to explore their own preferences in regard to evaluation criteria. It also helped decision makers better understand the results of GIS-based decision-making procedures.

In general, GIS-MCDA consists of the following elements (Malczewski, 1999):

1. Criteria identification
2. Criteria standardisation
3. Definition of criteria weights
4. Combining criteria
5. Interpretation of solutions and ranking alternatives
6. Sensitivity analysis

3.2.1 Identify the criteria relevant to the decision problem

Criteria within MCE are presented on a criterion map (GIS data layers). Criterion maps are usually classified into two groups. An *evaluation criterion map* represents a geographical attribute used to evaluate the performance of an alternative. On the other hand, the second group gives non-feasible alternatives, usually through *constraint maps* that present the limitations that will remove certain alternatives from consideration. In this step it is necessary to identify the feasible space for alternatives. This is done through a combination of both GIS groups (maps).

It is important to define the feasible space for alternatives in this step and before criterion standardisation has been completed. In many studies the feasible space is defined at a later stage of MCE which, according to Malczweski, is not the correct order. It is been shown that the output results differ significantly if feasible space is defined in the later stages (Malczewski, 2000). This is especially important when suitable cells should be ranked in the analysis, because a different ranking of alternatives occurs when feasible cells are generated first compared to at a later stage.

There are 3 common techniques used in criteria selection: *examination of the relevant literature*, *analytical study* and *survey of opinions* (Malczewski, 1999; Malczewski & Rinner, 2015).

3.2.2 Conduct criterion standardisation

When performing GIS-MCE, the criteria (GIS layers or criterion maps) involved in the analysis usually have different measurement scales, depending on which the criterion maps can be either *qualitative* or *quantitative* (Malczewski, 1999; Malczewski & Rinner, 2015). Examples of qualitative criterion maps are GIS layers presenting soil and vegetation types, while quantitative criterion maps could show a digital elevation model and temperature. Because different scales of attribute values are involved, criterion maps must be translated into comparable units; in other words, criteria need to be standardised. Methods usually used for criterion standardisation are as follows:

- *linear scale transformation (the maximum score and the score range procedure)*
- *fuzzy membership functions*
- *expert opinion*

Each method has its own advantages and disadvantages. Up to now, the linear scale transformation method has been used the most in the GIS-MCE approaches (Malczewski, 1999; Malczewski, 2000). Detailed descriptions of the above-mentioned methods can be found in (Malczewski, 1999; Malczewski & Rinner, 2015).

3.2.3 Definition of criteria weight

In this step it is necessary to define the criterion weights, which are used to attribute more or less importance to a specific criterion. Several MCE techniques have been proposed for the weight assignment.

In particular, the following techniques help in defining criterion weights (Malczewski, 1999; Greene, 2011):

- *ranking methods – rank sum, rank reciprocal and rank exponent method,*
- *rating methods (point allocation approach and ratio estimation procedure),*
- *Analytical Hierarchy Process – AHP,*
- *Analytical Network Process – ANP as a generalisation of AHP.*

Among the above-mentioned techniques, the Analytic Hierarchy Process (AHP) and Analytical Network Process (ANP) are mostly applied within GIS-MCE (Malczewski & Rinner, 2015). Both use the pairwise comparison method. One of the assumptions in AHP is that the elements in a hierarchical structure are independent. ANP is then applied to tackle the presence of dependency. These methods were originally developed by Saaty in 1980 (Saaty, 1980). According to empirical applications, it has been suggested that the pairwise comparison methods are the most effective.

The AHP approach is used in this thesis. Thus, a more detailed mathematical theory background of AHP is described below.

Analytical Hierarchy Process (AHP)

The pairwise comparison method was developed in the context of the Analytic Hierarchy Process (AHP) and mainly used to define criteria weights logically consistent and mathematically defensible (Malczewski & Rinner, 2015; Jeffry, 2012). It includes several steps shown in Figure 4 below:

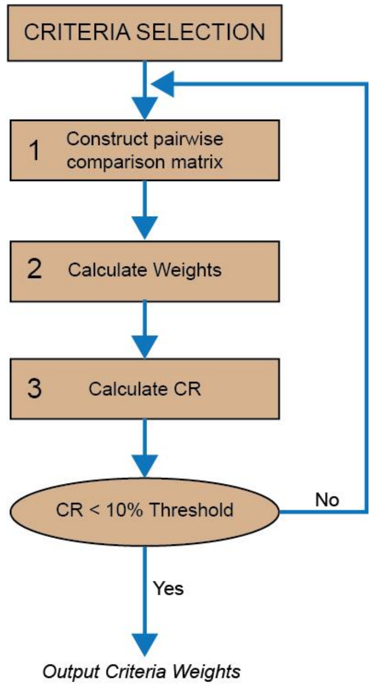

Figure 4. Steps to conducting Analytical Hierarchy Process – AHP (adapted from Chen et al., 2010)

1. <u>Construct the pairwise comparison matrix, A</u>

Pairwise comparison matrix A is $(n\ x\ n)$ order (n – denotes the number of compared criteria). Matrix A contains the elements a_{ij} and can be defined as follows:

$$A = [a_{ij}], \ \ i, j = 1, 2, 3, \ldots.., n$$

– a_{ij} are the elements (preferences of one criterion over another)

Matrix A has the property of reciprocity, expressed as:

$$a_{ij} = \frac{1}{a_{ji}}$$

To express the preferences of one criterion over another, the assessment values ranging from 1 to 9 are used. What these values represent is presented in Table 2. A decision maker usually fills the pairwise comparison matrix with these values. Because of assumed reciprocity, if a criterion "A" is twice as preferred as criterion "B", then it can be concluded that criterion "B" is preferred only half as much as criterion "A". Once the preference has been entered into the matrix, its reciprocal value is automatically entered in the corresponding cell.

Table 2. Various states for pairwise comparison and their numerical rates

Intensity of importance	Definition
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to extremely strong importance
9	Extreme importance

For example, if 3 criteria are considered, then pairwise comparison matrix A looks like the following:

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$$

2. <u>Calculates criteria weights, Wi</u>

Creation of normalised pairwise comparison matrix B is as follows:

$$B = [b_{ij}], \qquad i, j = 1, 2, 3, \dots, n$$

$-$ b_{ij} are the elements of normalised pairwise comparison matrix B

Elements b_{ij} of normalised pairwise comparison matrix B are found by dividing each element a_{ij} of pairwise comparison matrix A by the corresponding column sum representing elements belonging to that column – $\sum_{i=1}^{n} a_{ij}$.This is accomplished by applying the following formula:

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}, \qquad i, j = 1, 2, 3, \dots, n$$

With the above-mentioned example, when 3 criteria are taken into consideration, normalised pairwise comparison matrix B is as follows:

$$B = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix}$$

To define the weighted matrix W that has weight W_i of each criterion, it is necessary to find the average values across every row of normalised pairwise comparison matrix B. This is accomplished using the following formula:

$$W_i = \frac{\sum_{j=1}^{n} b_{ij}}{n}, \qquad i, j = 1, 2, 3, \dots, n$$

$-$ n is the number of criteria

With the example of 3 criteria the weighted matrix W is as follows:

$$W = \begin{bmatrix} W_1 \\ W_2 \\ W_3 \end{bmatrix}$$

3. Calculate consistency ratio, (CR)

Because human judgement is involved in the comparison process, it is necessary to check the consistency of the estimated criterion weights. An example of a consistency statement is as follows: criterion "A" is better than criterion "B", criterion "B" is better than criterion "C", thus "A" is better than "C". However, when there are lots of criteria, it might be difficult to notice these conditions. Thus, the consistency ratio could be used to check if this transitive property of the matrix exists. In other words, the consistency ratio checks if a decision maker has sufficiently thought through their decision to prefer one criterion over another.

Calculating the consistency ration involves:

- Determination of *weight sum vector* – $\{W_{sumi}\}$:

$$\{W_{sumi}\} = [a_{ij}] \times \{W_i\}$$

$-$ $[a_{ij}]$ is the pairwise comparison matrix, defined in step 1
$-$ $\{W_i\}$ is the weight vector, calculated in step 2

In the example with 3 criteria, this step can be presented as follows:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \text{ x } \begin{bmatrix} W_1 \\ W_2 \\ W_3 \end{bmatrix} = \begin{bmatrix} a_{11}W_1 + a_{12}W_2 + a_{13}W_3 \\ a_{21}W_1 + a_{22}W_2 + a_{23}W_3 \\ a_{31}W_1 + a_{32}W_2 + a_{33}W_3 \end{bmatrix} = \begin{bmatrix} W_{sum1} \\ W_{sum2} \\ W_{sum3} \end{bmatrix}$$

- Determination of consistency vector – $\{Cons_i\}$ as follows:

$$\{Cons_i\} = \{W_{sumi}\} \times \left\{\frac{1}{W_i}\right\}$$

$-$ $\{W_{sumi}\}$ is previously calculated weight sum vector
$-$ $\{W_i\}$ is weight vector, calculated in step 2

In the example with 3 criteria, the calculation of consistency vector looks like the following:

$$\begin{bmatrix} C_{cons1} \\ C_{cons2} \\ C_{cons3} \end{bmatrix} = \begin{bmatrix} W_{sum1} * \frac{1}{W_1} \\ W_{sum2} * \frac{1}{W_2} \\ W_{sum3} * \frac{1}{W_3} \end{bmatrix}$$

- <u>Determination of the average λ_{max} of the elements of consistency vector – $\{Cons_i\}$ as follows:</u>

  λ_{max} is the principal eigenvalue and represents the maximum eigenvalue of $(n\ x\ n)$ reciprocal pairwise comparison matrix A. Saaty has shown that in a consistent matrix[2] the largest eigenvalue - λ_{max} is equal to the number of comparisons - n in a comparison matrix (Saaty, 1986). In other words, the consistent matrix (comparison matrix with precise results) has the following property: $\lambda_{max} = n$. For an inconsistent matrix, where human judgment is involved, the following statement is true: $\lambda_{max} \geq n$. Thus, λ_{max} needs to be calculated so it can be compared with the value of n as the difference between the two is an indication of inconsistency.

$$\lambda_{max} = \frac{\sum_{i=1}^{n}(Cons_i)}{n}$$

  $-$ $(Cons_i)$ are elements of consistency vector – $\{Cons_i\}$
  $-$ n is number of criteria

- <u>Determination of *Consistency Index*, CI as follows:</u>

  To measure the consistency of the subjective judgment, meaning to define the deviation or degree of consistency, the Consistency Index (CI) is calculated. The higher the value of this index, the greater the inconsistency in the estimate. This is shown through the value of $(\lambda_{max} - n)$ in the equation that follows. In other words, this value represents the departure of consistency as it measures the deviation of the inconsistent matrix from the total consistent comparison matrix.

$$CI = \frac{(\lambda_{max} - n)}{(n-1)}$$

  $-$ λ_{max} is the average of the elements of the consistency vector – $\{Cons_i\}$
  $-$ n is number of criteria

[2] The total consistent matrix is the matrix in which the elements, which are compared, are expressed in the same units of measurements and values of the elements obtained through precise measurements. Thus, there is no inconsistency in such a comparison matrix.

- Determination of the *consistency ratio*, CR as follows:

  In order to obtain the real measure of the consistency, the computed Consistency Index (CI) in the previous step needs to be compared to the Consistency Index obtained if the comparison in the comparison matrix is preformed at random. The Consistency Index so obtained is called the Random Consistency Index (RI). Saaty calculated this index using a large sample of random matrices (over 500) with an increasing number of elements n (shown in Table 3). As the computed value of CR increases, so does the inconsistency as more randomness is present in the comparison.

$$CR = \frac{CI}{RI}$$

  $-$ CI is Consistency Index

  $-$ RI is Random Consistency Index value determined from Table 3.

Table 3. Random Consistency Index RI

N	RI	N	RI
1	0.00	8	1.41
2	0.00	9	1.45
3	0.58	10	1.49
4	0.90	11	1.52
5	1.12	12	1.54
6	1.24	13	1.56
7	1.32	14	1.58

Finally, if the computed consistency ratio is less than or equal to 0.10 ($CR \leq 0.10$), the degree of consistency is satisfactory (Saaty, 2008). In case that the consistency ratio is equal to 0.0 then perfect consistency has been achieved. If the computed consistency ratio is greater than 0.10 ($CR > 0.10$) there is a serious inconsistency, and the criteria comparison has to recalculated. This means that new preference values are assigned and the process repeated until the consistency ratio reaches the required value.

The literature mentions several advantages of the AHP technique (Malczewski & Rinner, 2015): its straightforwardness and convenience, its simplicity in that only two criteria are considered at a time, and its consistency while performing evaluations. Finally, it has a theoretical background (decision theory) and has been tested theoretically and empirically in many studies.

On the other hand, one of its disadvantages relates to subjective evaluation. For example, there could be inconsistency imposed by a 1 to 9 scale. In addition, conflicts could exist between decision makers. Another disadvantage is that this method becomes complex if there are many criteria for comparison requiring time-consuming computations.

3.2.4 Combining criteria

Decision rule represents a method used to combine the criteria. In the GIS-MCDA approach, the following additive decision rules are widely used (Malczewski, 1999; Latinopoulos & Kechagia, 2015; Malczewski & Rinner, 2015).

- *weighted linear combination – WLC,*
- *value/utility function approaches and*
- *analytic hierarchy process – AHP*

Weighted linear combination (WLC) is the most often used of the above methods.

The literature usually uses other terms for this method, such as: simple additive weighting, weighted summation, weighted linear average and weighted overlay. This method is based on the weighted average approach. In the WLC method, the weight assigned to each criterion is multiplied by criterion (attributes) values. Then summing of the obtained products is performed and the alternative with the highest (benefit) or lowest (costs) score is chosen. The formula representing the weighted linear combination technique is as follows:

$$A_i = \sum_j w_j \, x_{ij}$$

$-\ w_j$ – normalised weight
$-x_{ij}$ – attribute transformed in comparable scale

Figure 5 shows an example of a WLC method, in which criterion map standardisation was completed by applying the linear-scale transformation approach. A cell value of ND means NoData for a particular cell.

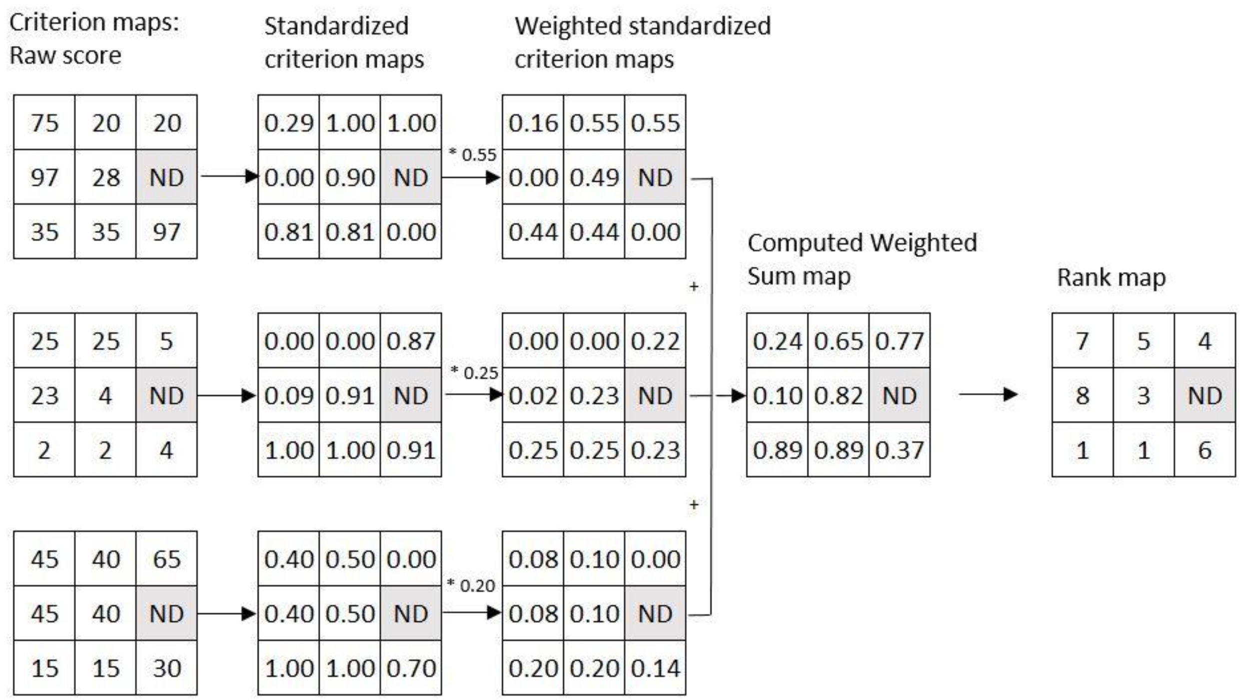

Figure 5. Weighted linear combination performed on raster datasets, (ND means NoData for the cell) (adapted from Belka, 2005)

This method is very attractive to decision makers due to its simplicity. However, it is prone to the *scale (resolution) and aggregation effect* (called the modifiable area unit problem) (Malczweski, 2000). In general, WLC assumes fixed spatial data meaning that the shape and size of alternatives are determined in advance. When one uses higher-resolution and more-disaggregated data, less bias is noticed. In that way, scale can significantly influence the results of WLC.

3.2.5 Conduct the comparison and ranking alternatives

The recommendation represents the result of the decision-making analysis and refers to actions that should be taken. It is made based on ranking the alternatives and conducting sensitivity analysis. The optimal alternative is usually described in detail. The recommendation could also be a group of candidates to be considered for implementation. The final recommendation is usually presented visually as this powerfully communicates the alternatives to decision makers and stakeholders.

3.2.6 Sensitivity analysis

Some parts of the GIS-MCE approach are prone to uncertainty, which can be classified into several types.

The first refers to a positional uncertainty seen when creating the geodatabase. Positional errors are errors in measurement between the true and measured value. Regarding the numerical data, *root mean square – RMS* is usually used to estimate the error. If the data are categorical, the errors are mainly presented by defining the confusion matrix (Kappa statistic).

Another error type can be related to decision-making preference as the decision maker's judgment is greatly involved in spatial multi-criteria decision making. In some cases a decision maker might have limited knowledge and imprecise information. Also opinions on criteria may differ between decision makers, which could cause imprecision.

Sensitivity analysis is mostly oriented towards criterion (attribute) values and weights. A sensitivity to the latter is the more important because weights in the GIS-MCE approach represent subjective numbers.

Decision makers often disagree about criterion weights. The sensitivity analysis, which takes criterion weights into consideration, is usually performed by making small changes in the criterion weights and checking how the output (alternatives) is sensitive to this change. If the rankings of alternatives remain the same when criterion weights are changed, it can be concluded that the errors in criterion weights are insignificant. On the other hand, if the ranking of alternatives greatly changes, the criterion weights should be carefully reconsidered.

3.3 Producing road alignments using GIS

Producing road alignments by applying GIS tools is called the *least-cost path analysis*. Among other uses, it is usually applied to define the best alignment for the new road in terms of construction costs. Two steps have to be completed.

<u>In the first</u> it is necessary to compute the least accumulative cost distance from a source input using the cost raster. Completing this step requires a source input, a cost raster, a cost distance measure and an algorithm used to define the least accumulative cost path (Belka, 2005; Hala & Hassan, 2013; Singh & Singh, 2017; Chang, 2018).

A <u>*source input*</u> can be either a raster or a feature dataset. If a source input is given as a raster dataset, then all cells containing a value are considered source cells. NoData should be assigned to all cells not considered source cells. If the source dataset is given as a feature dataset it will be internally converted to a raster dataset. The least-cost path is computed for every cell within the raster to the source cells.

A <u>*cost raster*</u> represents the cost (impedance) of travelling through each cell. Depending on the type of analysis, cost rasters are usually created by combing several raster datasets, representing different cost factors. These raster datasets (cost factors) could be expressed as actual or relative costs. Relative costs need to be further standardised by applying the reclassification technique to match the other raster datasets with actual costs, which are then combined to obtain the final cost raster.

The <u>*cost distance measure*</u> in the path analysis is based on the node-link cell representation within the raster dataset. Here node represents the centre of the cell. The centre of one cell is connected to the centre of the adjacent cell via a link, which could be either lateral or diagonal. A lateral link connects the node of one cell to 4 immediate neighbouring cells. A diagonal link connects the node of one cell to one of 4 corner neighbouring cells. This representation is shown in Figure 6. In a node-link cell representation, every node has a value from the cell it belongs to. Regarding the link has a cost of travel or resistance from one cell (node) to its adjacent cell (node).

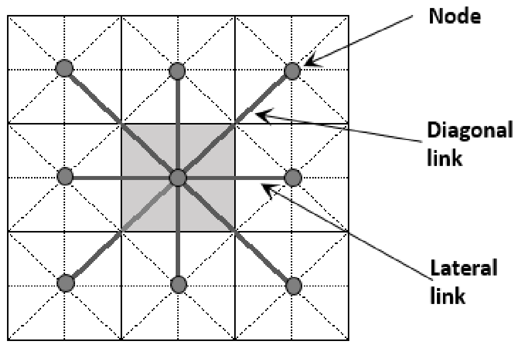

Figure 6. Node-link cell representation

For a lateral link a travelling cost (a1) is the cost distance of travelling through a lateral link (1.0 cell) multiplied by the average of the two cost values (cost1 and cost2). In this case, the cost of travelling (a1) could be expressed as follows:

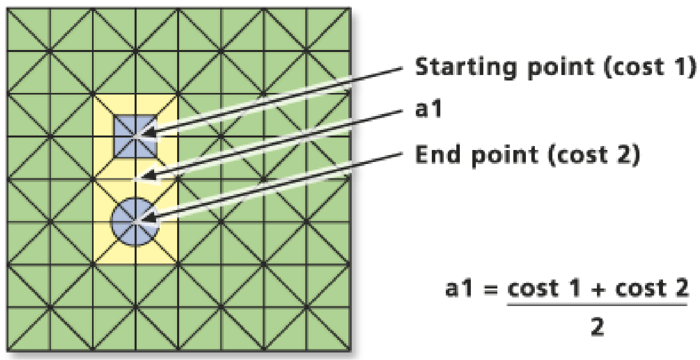

Figure 7. The cost of travelling between adjacent nodes through a lateral link

For a diagonal link, a travelling cost (a1) is the cost distance of travelling through a diagonal link (1.414 cells) multiplied by the average of the two cost values (cost1 and cost2), calculated as follows:

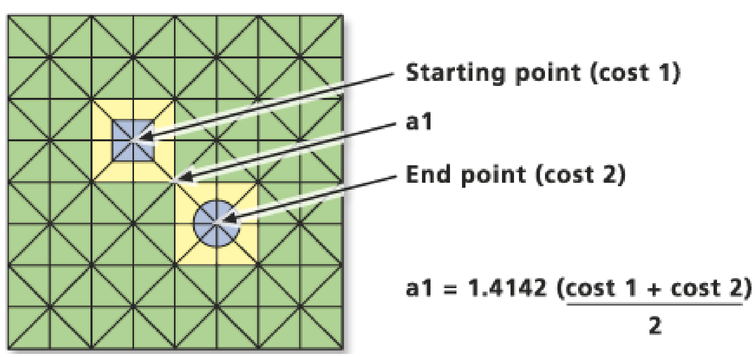

Figure 8. The cost of travelling between adjacent nodes through a diagonal link

Two non-adjacent cells can be connected with many different paths. To find the least accumulative cost path it is necessary to apply an *algorithm*.

This algorithm is based on Dijkstra's well-known algorithm and includes an iterative process. Firstly, source cells are located and zero values assigned to them. Then travelling costs for all adjacent cells travelling toward the source cells are assigned and the least-cost cell is selected and assigned to the output raster dataset. In the next step, it is necessary to check the accumulative cost for immediate-surrounding cells of the selected one. If the new recalculated accumulative cost is higher for a considered immediate cell, then the old cost is kept. Otherwise, it is replaced with this newly computed lower cost. In this process, cells already assigned to the output raster dataset are not recalculated. This entire procedure is repeated until all cells within the cost raster have an assigned least accumulative cost. The final output is a raster dataset showing the accumulative travelling cost for each cell to a source cell.

The first step can be done using GIS by applying the *Cost Distance* geoprocessing tool. The output represents the *cost distance* raster which gives the least accumulative cost distance from each cell to the defined source location. The least accumulative cost distance raster created here does not contain information on how to travel back to the source cell. To determine how to get from each cell, in which the least accumulative cost distance is stored, to the source cell, it is necessary to use the direction raster containing this information. The direction raster is called a *"back-link"* raster because every cell is linked back to the source cell. This direction raster is the second output of the *Cost Distance* geoprocessing tool. It shows the direction from each cell to the source cell. The algorithm computing the direction raster assigns a certain code, an integer from 0 to 8, to every cell within the direction raster, which gives the direction to the adjacent cell and thus back to the source cell.

In summary, the first step provides almost all of the information needed to produce the road alignment. What remains to be determined is the second point, a cell, from which the least-cost path is determined to the source cell. This is completed within the <u>second step</u>, which is performed by applying the *Cost Path* geoprocessing tool. The input for this tool is the cost distance raster and a backlink raster produced in the first step and the location from which this location will be connected to the source cell.

4 Data collection

Spatial data for the study area were available in the format of shapefiles and raster datasets. They were provided by the consulting company GISPlan in Gaborone. All datasets, except land cover type, were available in a local coordinate reference system for Botswana. The datasets used in this master thesis are presented in more detail below.

4.1 Slope of the terrain

The slope of the terrain was readily available as a raster dataset with cell size 5 x 5 meters. The slope for the Tlokweng study area is shown in Figure 9 below. As can be seen the terrain is quite flat. Approximately 75% of the area falls between extremely flat and gently undulating slopes (0.2% - 5.0%). Hilly areas with slopes steeper than 10% are mostly located in the southwestern part of the study area (GIS Plan, 2018).

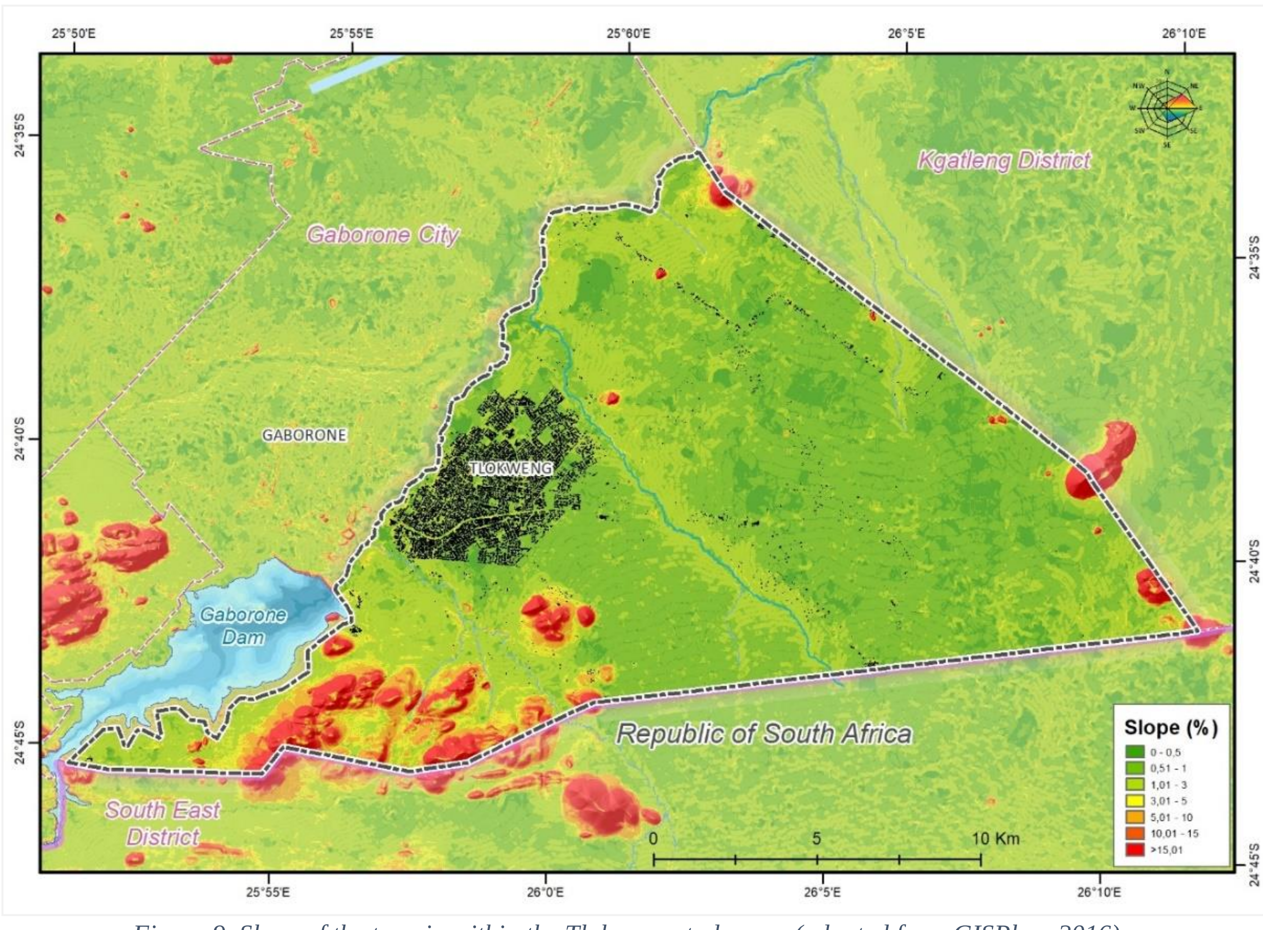

Figure 9. Slope of the terrain within the Tlokweng study area (adapted from GISPlan, 2016)

4.2 Existing road network

Figure 10 shows the existing road network in the Tlokweng study area. The existing roads are classified into 5 groups: primary, secondary, tertiary, access and tracks roads. The main primary road is Tlokweng road, which runs from the border with the Republic of South Africa through Tlokweng city and ends at Gabarone city centre. This road represents the main connection between the Republic of South Africa and Gaborone and is the most congested road in the study area. Especially the sections that run through the cities of Tlokweng and Gabarone are overburdened by traffic causing traffic jams during peak hours. Secondary, tertiary and access roads are primarily located in Tlokweng city centre. Tracks as the lowest road class run throughout the entire Tlokweng area.

Network data was available as a polyline feature dataset.

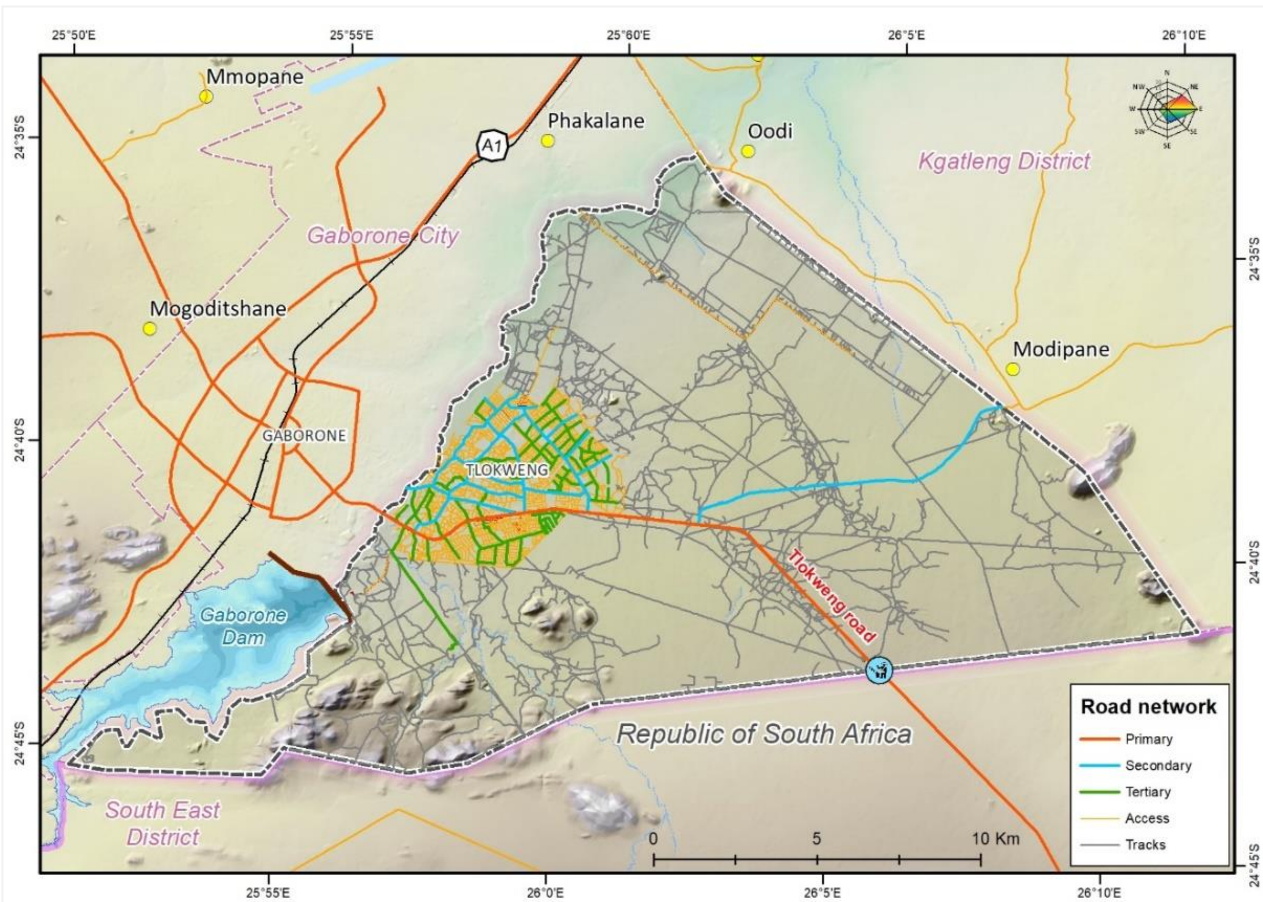

Figure 10. Existing road network within the Tlokweng study area (adapted from GISPlan, 2016)

4.3 Drainage order

Data representing the stream size according to the Strahler stream order were available as a polyline feature dataset. Strahler numbers refer to the Strahler stream order and are used to define stream size based on the hierarchy of tributaries. The first order tributary is typically the smallest in size. The higher the stream order, the larger the tributary.

The stream order in the Tlokweng is shown in Figure 11. It can be seen that the Notwane and Twane rivers are classified in the 6th Strahler stream order. The Maratadiba river partially belongs to the 6th and 7th Strahler stream orders.

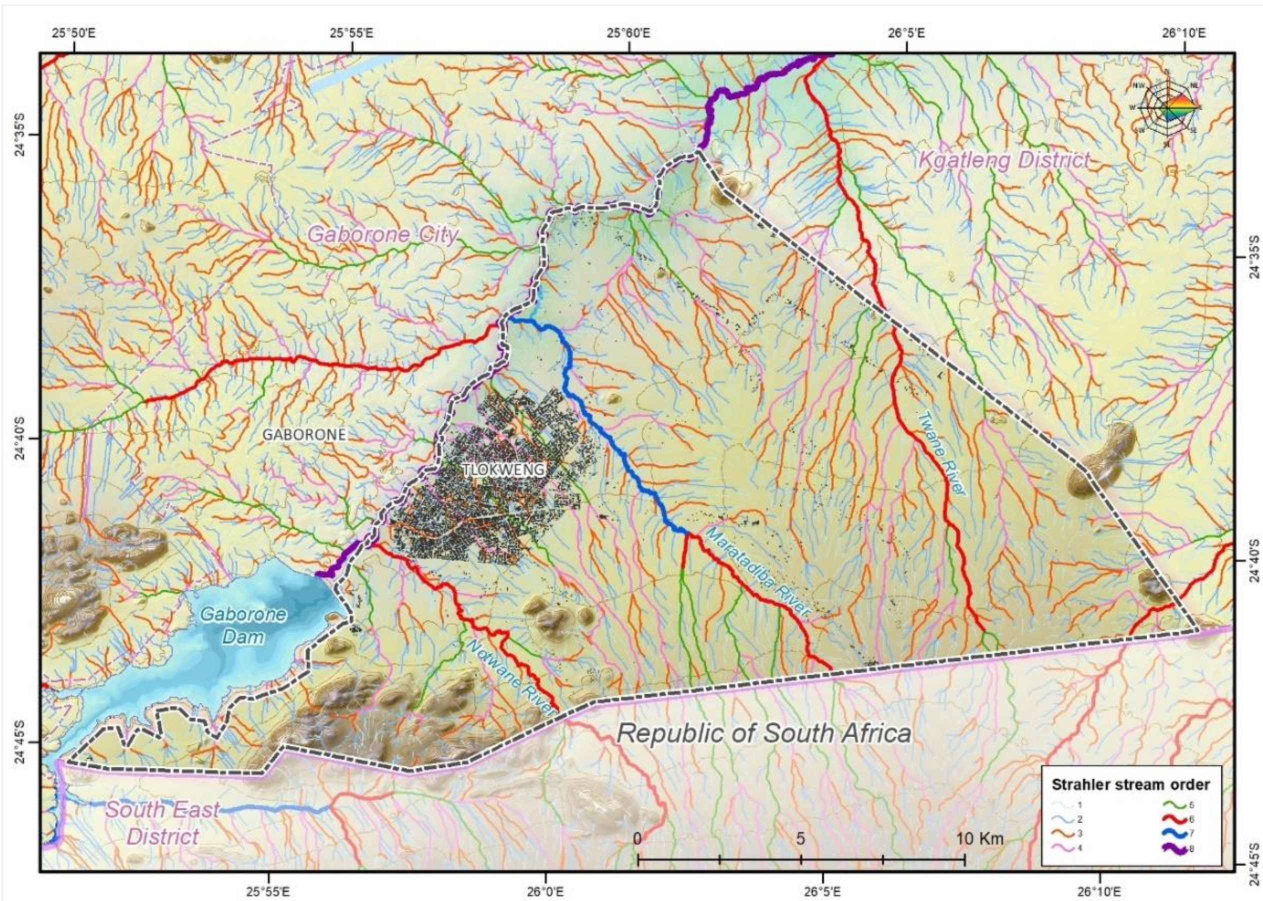

Figure 11. Strahler stream order within the Tlokweng study area (adapted from GISPlan, 2016)

4.4 Flooding areas

Flooding zones within the Tlokweng study area are shown in Figure 12. Flood hazards can be relatively high, considering the low rainfall in the area. The major floodplain is along the Notwane and Maratadiba rivers. During heavy rain, all major rivers, streams and rivulets are liable to cause flooding in adjacent areas. In 2016 unpredictable heavy rain caused flooding of large areas of Tlokweng (shaded light blue in Figure 12).

Flooding areas were available as a polygon feature dataset.

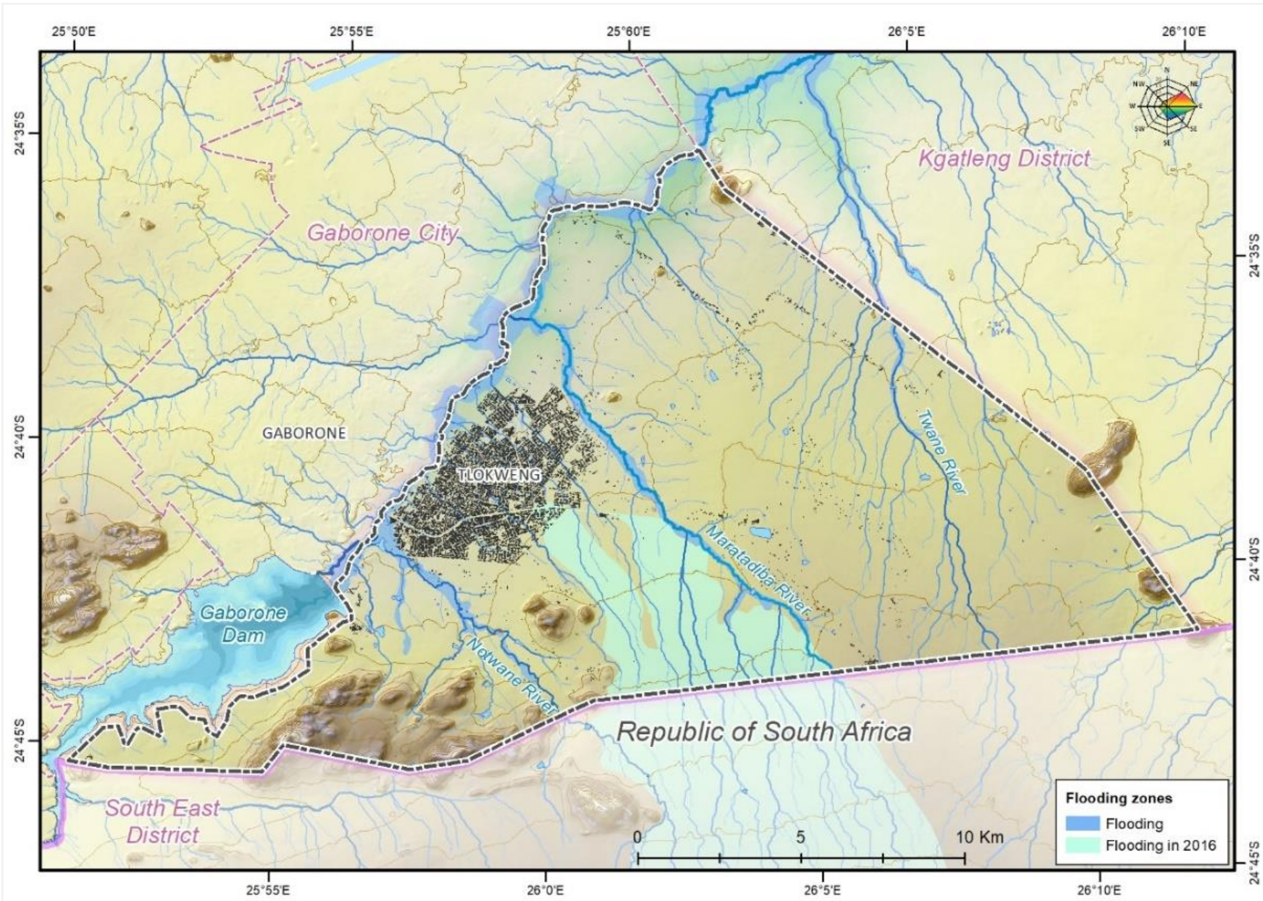

Figure 12. Flooding zones within the Tlokweng study area (adapted from GISPlan, 2016)

4.5 Geology type

Gaborone Thgama granite is the major lithological complex underlying the study area, covering approximately 80% of the area. Presently geological conditions with regards to building foundations and urban development in Tlokweng have generally remained good and do not pose serious constraints to development in Tlokweng.

Existing geology types within the Tlokweng study area are shown in Figure 13 and are available as a polygon feature dataset.

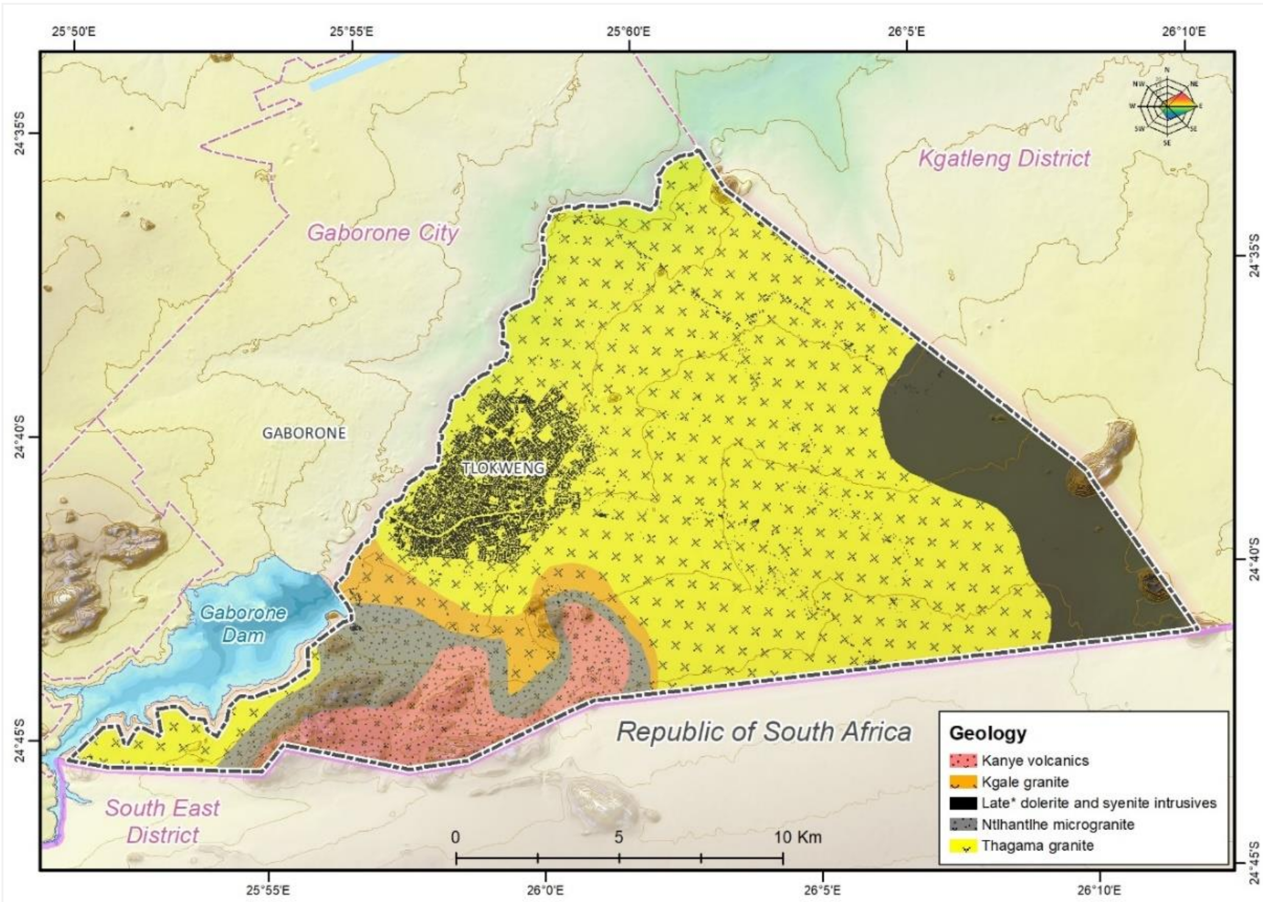

Figure 13. Geology type within the Tlokweng study area (adapted from GISPlan, 2016)

4.6 Soil type

Regarding soil types within the study area, only agricultural data are available. The data were defined following Food and Agriculture Organisation – FAO soil taxonomy (GIS Plan, 2018). However, it was still possible to draw conclusions about the performance of different soil types in respect to constructing a by-pass.

Prevailing soil types within the Tlokweng study area shown in Figure 14 and were available as a polygon feature datasets.

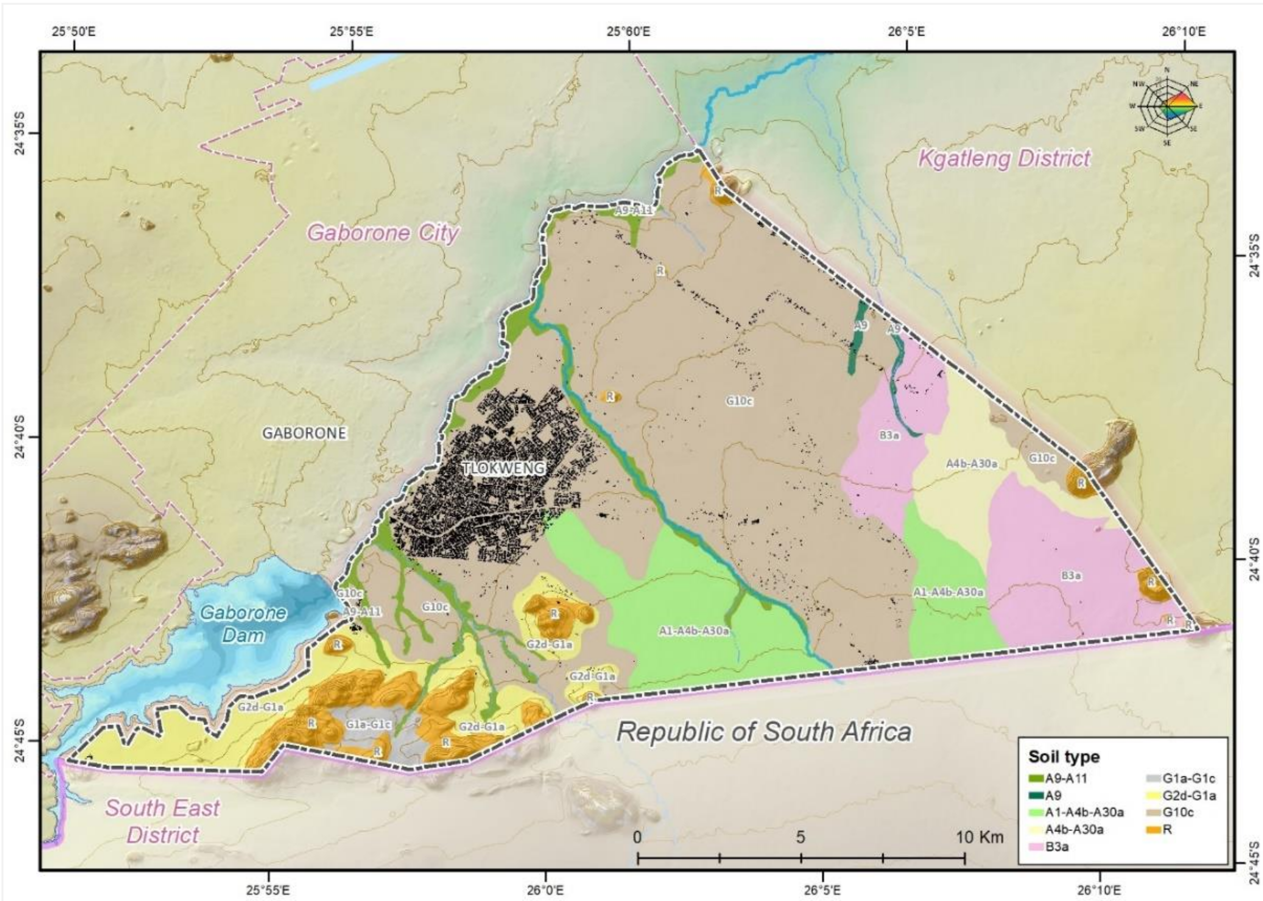

Figure 14. Existing soil type within the Tlokweng study area (adapted from GISPlan, 2016)

4.7 Land cover

There are currently eight distinctive land cover classes in the Planning Area, generated from the RCMRD (2010) and the USGS-Earth Explorer (2015) databases, as shown in Figure 15: sparse forest, open grassland, closed shrubland, open shrubland, woodland, cropland, water body and settlement. The most dominant are shrub lands, accounting for around 37% of the total area. Sparse forest and woodlands take up a combined 36% of the Tlokweng study area land mass. Land cover varies significantly between the southwestern, southern, western, northeastern and southeastern parts of the Tlokweng study area. The south west is mostly covered by sparse forest, woodlands and closed shrub lands. The south is dominated by cropland, with diminishing grasslands and surrounded by closed and open shrub land. The western part is dominated by the Tlokweng settlement.

Land cover was available as a raster dataset.

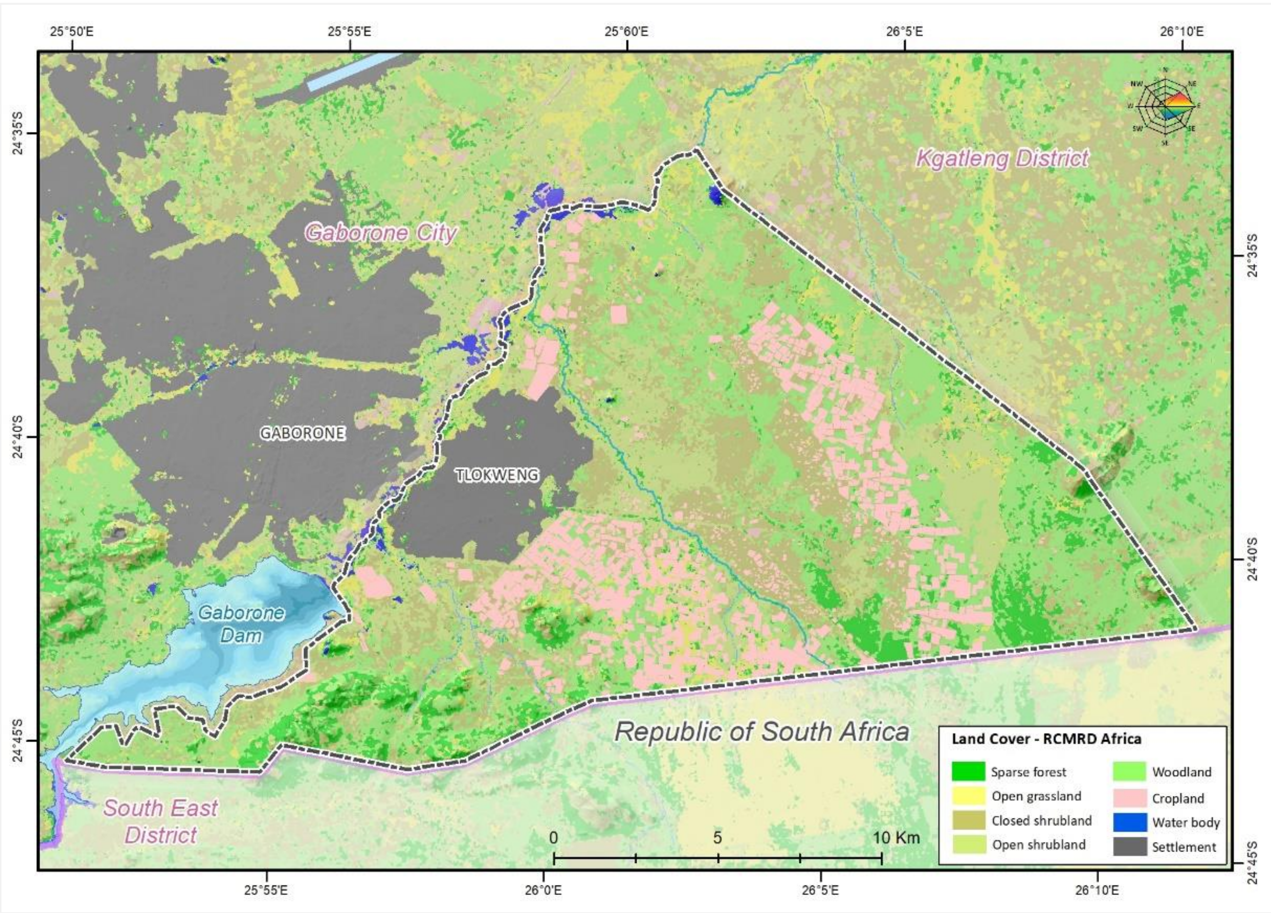

Figure 15. Land cover within the Tlokweng study area (adapted from GISPlan, 2016)

4.8 Land use

Existing land use in Tlokweng is shown in Figure 16. In general, land use types are classified as residential, commercial, civic and community, open space, recreational, industrial and agricultural. Residential land use is the most prevalent type in built-up areas. Single family residential (R1) represents the highest number of residential use types in built-up areas.

Land use types are available as a polygon dataset. Buildings in the form of polygons, normally too small to be included amongst land use types, are also shown in Figure 16.

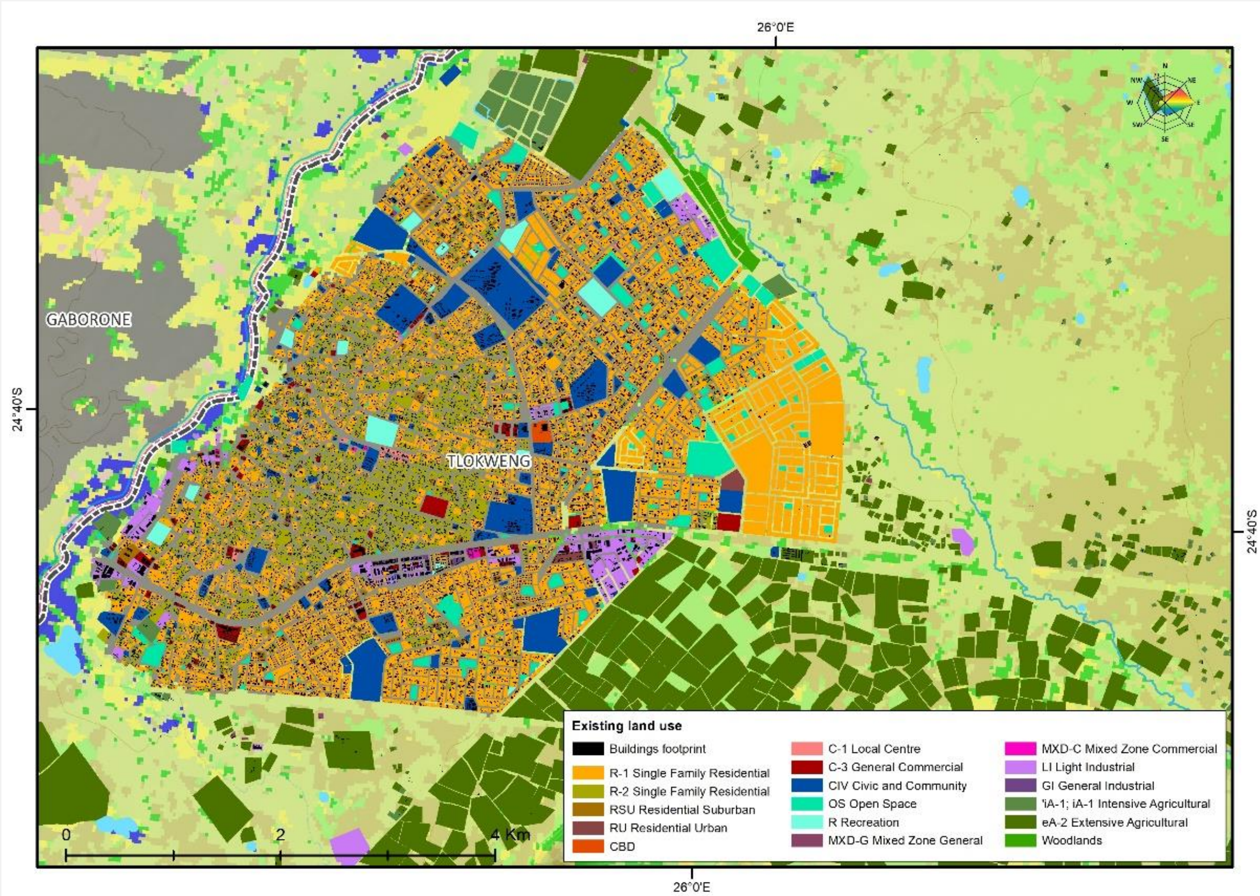

Figure 16. Existing land use within urban areas of the Tlokweng Planning Area (adapted from GISPlan, 2016)

4.9 Ground and surface water

Figure 17 designates those areas in the Tlokweng study area where underground water vulnerability is high. These areas are mostly found along and around the river systems. In these zones, any usage presenting a potential risk of groundwater contamination is prohibited.

Figure 17 also shows surface water – dams and ponds as an important surface water system. Gaborone dam located south of Gaborone is an important source of urban water supply for both Gaborone and Lobatese.

Ground and surface water data are available as a polygon dataset.

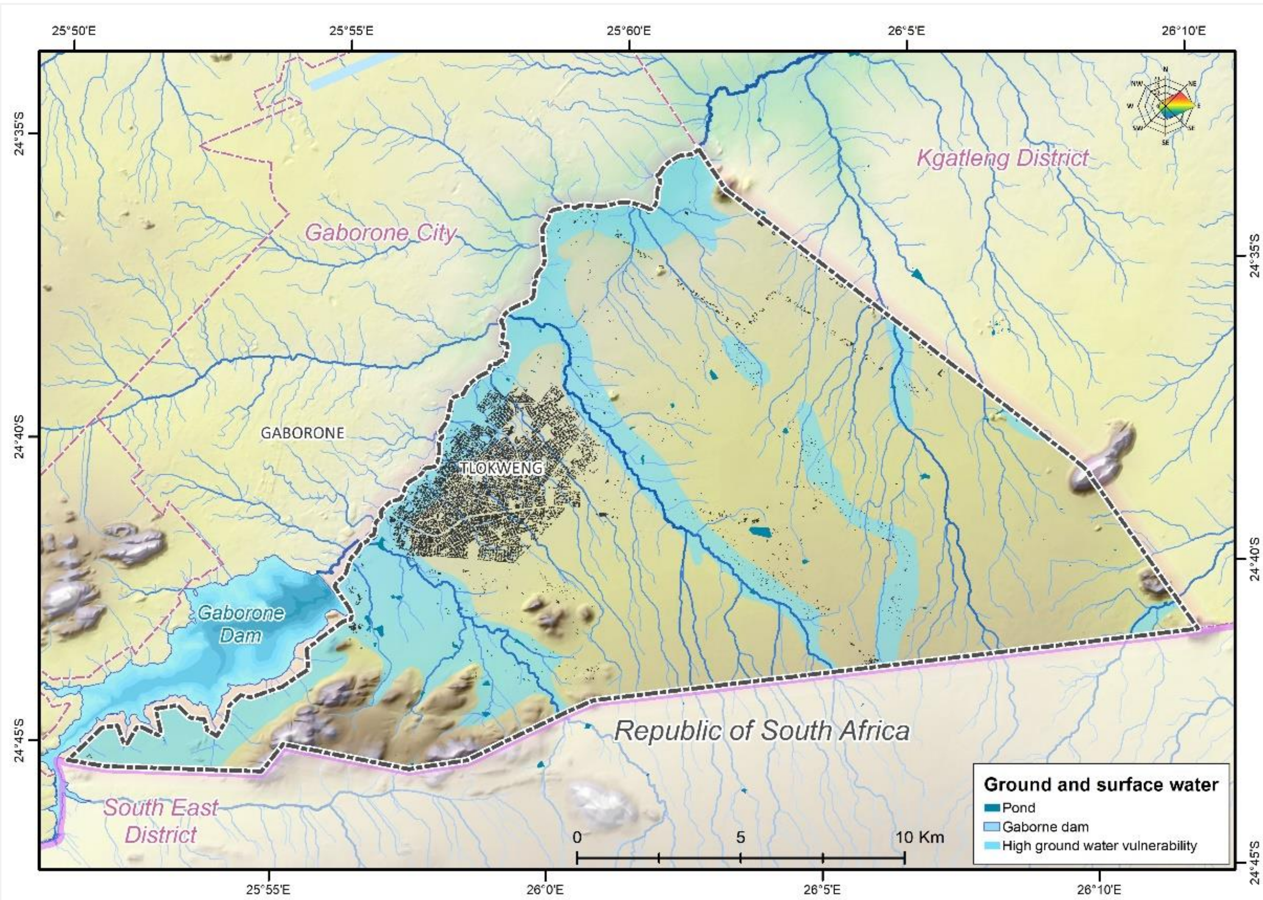

Figure 17. Highly vulnerable underground areas and surface water areas within the Tlokweng study area (adapted from GISPlan, 2016)

4.10 Spatial growth and natural protected areas

"Revision of the Tlokweng development plan (2001-2025)" presents different scenarios to accommodate the anticipated growth in Tlokweng by 2025. According to the spatial growth scenario the spatial expansion through urban development will be in two designated areas: southeast of the built-up area towards the Sefoke river and to the east of the built-up area. This option also presumes the development of a Special Economic Zone along the Zeerust Road, immediately before the border gate. The plan also proposes developing a natural protected tourism area along the banks of the Notwane river for leisure and recreational activities plus a cultural initiation site for the Batlokwa. The urban and economic expansion, and tourism areas are shown in Figure 18.

New expansion areas are given as a polygon dataset.

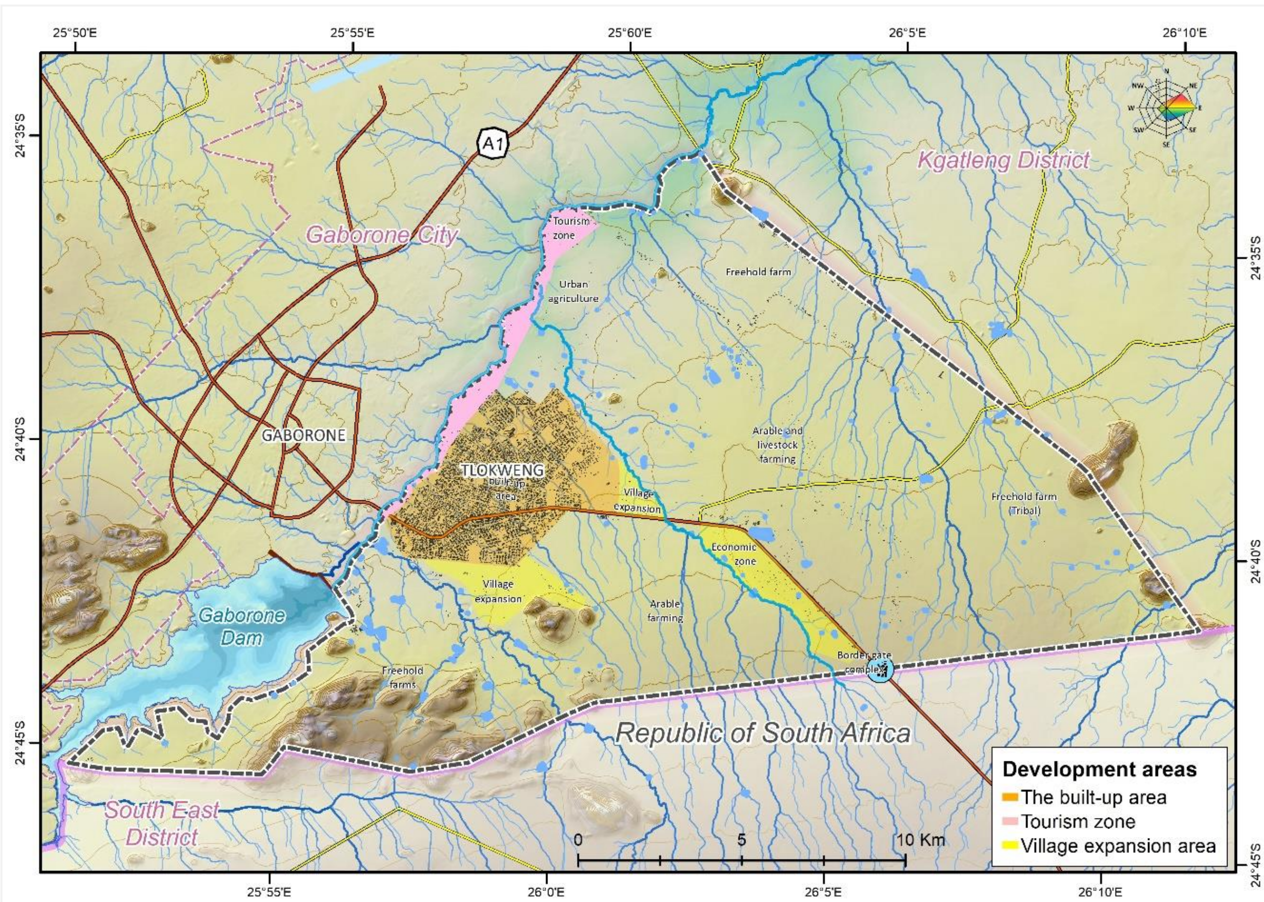

Figure 18. Development areas – village expansion areas, tourism and economic zone (adapted from GISPlan, 2016)

5 Methodology

The methodology chapter consists of 4 parts. Firstly, a detailed description of the model's construction is given. Secondly, more information is presented regarding the application of the model to the case study. The third part presents how the model validation is conducted. Finally, the sensitivity analysis is described in more detail.

5.1 Model description

Building the model consists of several steps, such as: criteria definition, data pre-processing, criteria standardisation, assigning weights to criteria and aggregation of criterion maps.

5.1.1 Criteria definition

Based on the literature review, an official government document for Botswana – *"Road Types and Geometric Design"* (Ministry of Transport & Communications, 2014) – and available filed survey spatial data, 13 criteria were defined as follows:

1. <u>Minimise unfavourable topographic conditions – slope of the terrain</u>

Slope is one of the crucial factors when defining road alignment. Linking only the row value of the slope to the cost necessary to overcome the slope would not be suitable because many different types of quantifications exist. At the same time it sounds reasonable to say that no costs will be posed by a 0 slope of the terrain, but as the slope gets steeper, by-pass road construction costs rise (Yashon et al., 2014).

2. <u>Minimise a number of by-pass crossings with roads with high priority</u>

The existing road network is an important factor since it will affect construction costs. If a by-pass intersects or passes too near to the primary road, for example, building complex interchanges and other road infrastructure will be required. This will affect construction costs.

3. <u>Minimise a number of by-pass crossings with rivers with high-order drainage</u>

Crossing rivers will require bridges to be constructed; therefore, it is important to take this criterion into consideration. More complex and costly bridges will be required for higher-order drainage.

4. <u>Maximise distance to flooding areas</u>

Road designers should be aware of potential flood areas that experience especially intense precipitation. These areas should be avoided as much as possible as they can stop traffic and increase construction and maintenance costs.

5. <u>Maximise construction suitability in respect to terrain geology</u>

This criterion is related to construction costs and refers to excavation, cut-and-fill works, etc. The effect on costs depends on rock type. For example, compact and hard rock (granite and gneiss) impose higher costs.

6. *Maximise construction suitability in respect to prevailing soil type of the terrain*

Soil covers the ground from the surface down to the underlying rock. Unstable soil types, such as sand and clay, should be avoided as much as possible. On the other hand, more-stable soil types such as loam are more suitable because they minimise both construction and maintenance costs.

7. *Maximise distance to natural protected areas*

It is important to protect areas such as agricultural land, grazing areas and valuable flora and fauna. In general, such places are of high value especially for farming and tourism. This criterion refers to environmental protection.

8. *Maximise distance to major river streams*

Fuel, emissions and contaminants from roads cause damage to surface streams, roadside soil, vegetation and trees. River pollution can cause degradation of aquatic ecosystems. To protect the water streams, road-alignment planners should take this criterion into consideration.

9. *Maximise distance to surface waters – dams and ponds*

Roads present a risk to drinking water resources because of vehicle emissions and hazardous spills. Therefore, it is important to protect surface water bodies as they are the main sources of drinking water in Tlokweng. Avoidance of surface waters is a criterion that refers to environmental protection.

10. *Maximise distance to ground waters*

Similar to surface waters, roads present a serious pollution threat to groundwater. Contaminants are deposited on roadway surfaces by traffic and during rainy seasons rainwater transports the contaminants to water bodies. Major vehicle accidents represent a particular threat such as overturned petrol trucks leaking fuel that makes it way to ground waters. Thus, great care is needed to protect water resources from such hazards.

11. *Prioritise arable, grazing, forest and built-up land*

It is necessary to consider land use and land cover when determining the impacts of a proposed by-pass on the surrounding environment and in calculating the compensation for land acquisition. The great importance of this criterion is that it will place a high degree of preference on protecting agricultural land within the Tlokweng study area. This criterion also considers both, urban (built-up) and non-urban areas in the Tlokweng study area.

12. *Maximise distance to residential areas to reduce air pollution*

This criterion refers to noise pollution in residential areas. Heavy traffic streams, particularly in urban areas, can generate significant emissions affecting air quality, which can be detrimental to the environment and public health.

13. *Maximise distance to residential areas to reduce noise pollution*

Noise pollution from traffic has been proved to have many harmful effects on human life. It can have both, physical and psychological consequences negatively affecting human health and behaviour.

The above-listed criteria are further classified into 3 umbrella themes depending on the criterion focussed on. As mentioned, an Environmental Impact Assessment (EIA) includes criteria from economic, environmental and social perspectives, grouped according to these 3 perspectives. In this thesis every perspective is called a theme.

Applying constraint criterion map

Before combining criteria within each theme by standardising and assigning certain weights, the constraint criterion map was used to determine areas where road alignment cannot pass through (infeasible alternatives). The constraint criterion map includes the areas of future urban expansion and the economic zone. This was performed using the *Raster Calculator* geoprocessing tool. The constraint criterion map receives Boolean values of *1* (true – feasible alternatives) and *0* (false – infeasible alternatives, the space where new urban areas and the economic zone are located). In the Raster Calculator, the condition statement was applied in the following form:

- *Con (Constraint Criterion Map, Standardised (Reclassified) Criterion Map)*

Criteria are summarised in Table 4. Constraint criteria are presented in Table 5.

Table 4. List of criteria, themes and datasets

#	Criteria	Theme	Data
1	Minimise unfavourable topographic conditions – slope of the terrain	Economy	Raster dataset representing slope of the terrain
2	Minimise a number of by-pass crossings with roads with high priority	Economy	Polyline dataset representing the existing road network
3	Minimise a number of by-pass crossings with rivers with high-order drainage	Economy	Polyline dataset representing the drainage order
4	Maximise distance to flooding areas	Economy	Polygon dataset representing flooding areas
5	Maximise geological construction suitability	Economy	Polygon dataset representing geology type
6	Maximise soil construction suitability	Economy	Polygon dataset representing soil type
7	Maximise distance to natural protected areas	Environmental	Polygon dataset representing areas with parks, flora and fauna
8	Maximise distance to fragile water streams	Environmental	Polyline dataset representing rivers
9	Maximise distance to surface waters – dams and ponds	Environmental	Polygon dataset representing dams and ponds
10	Maximise distance to ground waters	Environmental	Polygon dataset representing underground waters
11	Prioritise arable, grazing, forest and built-up land	Social	Raster dataset representing land cover; Polygon dataset representing land use; Polygon dataset representing buildings
12	Maximise distance to residential areas to reduce air pollution	Social	Polygon dataset representing residential areas in the Tlokweng urban area; Polygon dataset representing future urban expansion areas
13	Maximise distance to residential areas to reduce noise pollution	Social	Polygon dataset representing residential areas in the Tlokweng urban area; Polygon dataset representing future urban expansion areas

Table 5. List of constraint criteria

#	Constraint criteria	Theme	Data
1	Road alignment cannot pass through new urban expansion and economic areas	Constraint	Polygon dataset representing future urban expansion and economic areas

5.1.2 Data pre-processing

There was a need to pre-process some data for use in the analysis.

Polyline dataset representing the existing road network

The existing road network dataset is available as a shapefile – polyline data format. Pre-processing this dataset includes using geoprocessing tools such as *buffer*, *union* and *dissolve.*

The buffer geoprocessing tool is applied to create polygons around the existing road network. Roads belonging to higher road-hierarchy classes receive greater buffering distances with the tool.

Table 6 shows the distance values used by the buffer tool depending on road class. The used distance values were based on expert opinion.

Table 6. Distances used by the buffer tool depending on road class

Road class	Distance in buffer tool (m)
Primary	30.0
Secondary	15.0
Tertiary	9.0
Access	7.5
Track	3.0

After creating polygons around different road classes, some polygons overlap. For example, the polygon representing the "secondary" road class overlaps that representing the "primary" road class (see Figure 19). Thus, it was necessary to use the union tool to identify these overlapping areas (see Figure 20). The idea is that overlapping areas should belong to the highest road class involved in the overlap.

Finally, the dissolve tool was used to assign overlapping areas to the higher road class in the overlap (see Figure 21).

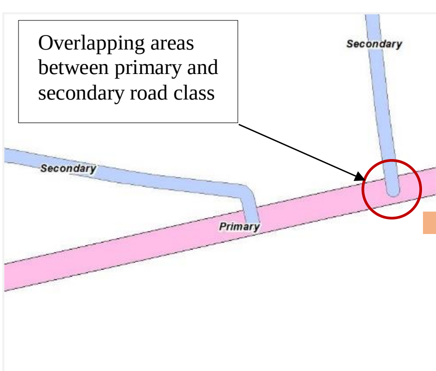

Figure 19. Buffer tool applied to primary and secondary road class

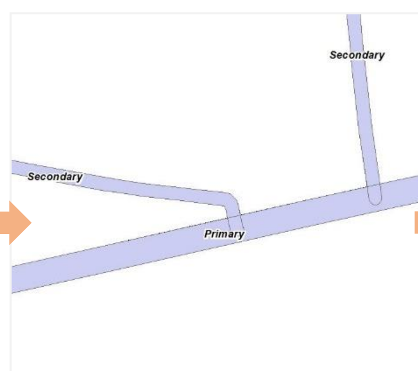

Figure 20. Union tool applied between primary and secondary road class

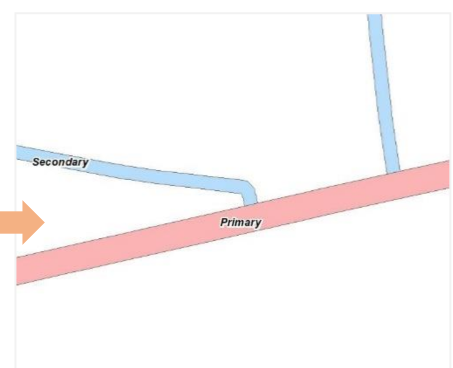

Figure 21. Dissolve tool applied to primary and secondary road class

Polyline dataset representing the drainage order

The drainage systems in the Tlokweng study area are described using the Strahler stream order. As mentioned, the dataset describing drainage order is given as a shapefile – polyline data format. Similar to the road network dataset, the same steps are applied for the existing drainage order. First, the buffer tool is used to make polygons differentiating different Strahler stream orders. The higher stream order receives the greater distance in the buffer tool (see Table 7). Then the union and dissolve geoprocessing tools were applied.

Determination of the distance used in the buffer tool was based on expert opinion.

Table 7. Distances used in the buffer tool depending on Strahler stream order

Strahler stream order	Distance in buffer tool (m)
1st	3.0
2nd	6.0
3rd	12.0
4th	25.0
5th	37.0
6th	50.0
7th	63.0
8th	75.0

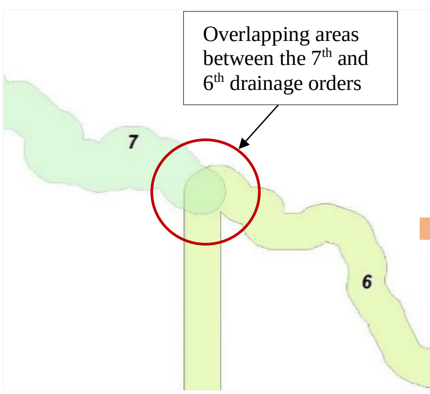

Figure 22. Buffer tool applied between the 6th and 7th Strahler stream orders

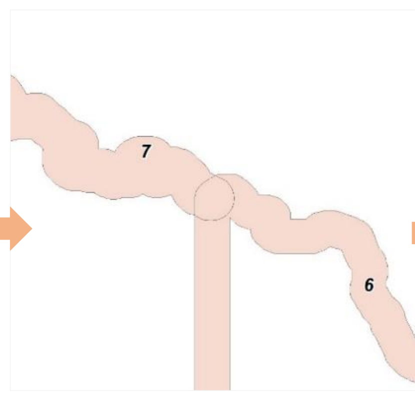

Figure 23. Union tool applied between the 6th and 7th Strahler stream orders

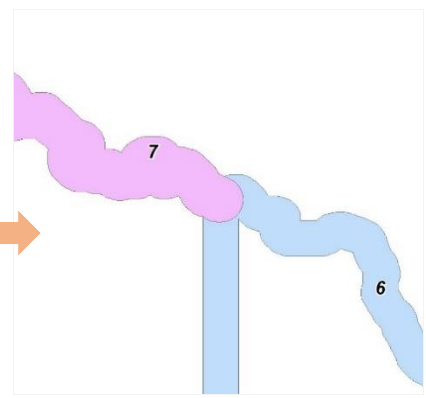

Figure 24. Dissolve tool applied to the 6th and 7th Strahler stream orders

Raster dataset representing land cover, land use and buildings

The land cover dataset was re-projected onto the local coordinate system used for the Tlokweng study area – Botswana.

Polygon datasets, representing land use and buildings, were converted to raster datasets using s geoprocessing tool – *"Polygon to Raster"*. Defined cell size within this tool was 5 metres. Finally, these 3 raster datasets – land cover, land use and buildings – were merged using the *"Raster Calculator"*.

5.1.3 Standardisation of criteria

For criteria to be comparable, it is necessary to perform criterion standardisation. Through the standardisation process every criterion map is translated to a comparable unit. A scale from 1 to 5 was used to standardise every criterion. An assigned value of 1 represents the most preferable choice (least cost), with 5 the least preferable (highest cost). To perform standardisation every criterion is presented with different classes and then each class is assigned a value from 1 to 5.

Classes and the decision of assigning the criterion values are based on expert opinion – in this case a faculty member specialising in road design and planning.

Within ArcGIS, the "Reclassify" geoprocessing tool was utilised to perform the assignment. Listed below are the different classes and costs assigned to each for every criterion.

1. *Minimise unfavourable topographic conditions – slope of the terrain*

Table 8 shows 5 different classes and the corresponding cost assigned to each. It is assumed that the costs are higher as the terrain slope steepens (Yashon et al., 2014). To build the road on hilly areas will require more complex construction work (for example, tunnels and bridges) which in turn will increase costs. Therefore, the most preferable terrain for road alignment has a slope between 0 and 3%. The least preferable terrain has a slope steeper than 12%.

Table 8. Slope classes and corresponding costs used in the Reclassify tool

Slope class (%)	**Cost**
0 – 3	1
3 – 5	2
5 – 8	3
8 – 12	4
> 12	5

2. *Minimise unfavourable topographic conditions – slope of the terrain*

Table 9 shows 5 road classes together with their assigned cost. The higher the road class, the higher the assigned cost. A higher road class will require more complex and costly intersections.

Table 9. Road classes and corresponding costs used in the Reclassify tool

Road class	**Cost**
Primary	5
Secondary	4
Tertiary	3
Access	2
Track	1

3. *Minimise a number of by-pass crossings with rivers with high-order drainage*
Table 10 shows 8 classes of the Strahler stream order and their assigned costs. The higher the stream order, the greater the cost because of the increased complexity of the bridge construction.

Table 10. Strahler stream orders and corresponding costs used in the Reclassify tool

Strahler stream order	**Cost**
1st	2
2nd	3
3rd	3
4th	4
5th	4
6th	5
7th	5
8th	5

4. *Maximise distance to flooding areas*
Table 11 shows classes expressed as a distance from flooding areas and costs assigned to them. As the distance from flooding areas gets higher, the assigned cost decreases. As mentioned, in 2016 heavy rains caused flooding in a large area in southern Tlokweng. Because this is a potential flood area, which is not flooded on regular basis, the assigned cost to this entire area is 3.

Table 11. Distance from flooding areas and corresponding costs used in the Reclassify tool

Distance (m)	**Cost**
0 – 100	5
100 – 200	4
200 – 300	3
300 – 400	2
> 400	1
Flooding in 2016	**Cost**
Entire area	3

5. *Maximise construction suitability in respect to geology of the terrain*
The costs assigned to different rock types are shown in Table 12 below. The higher costs were assigned to more-solid and stronger rock types, as more-complex and costly construction will be required.

Table 12. Rock types and corresponding costs used in the Reclassify tool

Rock type	Cost
Thagama granite	1
Kgale granite	2
Ntlhantlhe microgranite	3
Kanye volcanics	4
Late dolerite and syenite intrusive	4

6. *Maximise construction suitability in respect to prevailing soil type of the terrain*

The costs assigned to different soil types are presented in Table 13 below. Soil types more suitable for road construction have lower cost.

Table 13. Soil types and corresponding costs used in the Reclassify tool

Soil type	Cost
G10c Ferric luvisol	1
A1 – 4b – 30a - Pelic vertisol-Calcic cambisol – Vertic calcalic glaysol	2
G2d – G1a Ferric luvisol - Eutric regosol (lithic)	3
A4b – A30a Calcic cambisol- Vertic calcalic glaysol	4
A9 Calcic luvisol	4
A9 – A11 Calcic luvisol - Ferric luvisol	4
B3a Chromic luvisol	4
G1a – G1c Eutric regosol (lithic-shallow petric)	4
R Lithic leptosol	5

7. Maximise distance to natural protected areas

Different distance classes and their corresponding costs are given in Table 14. The cost decreases as the distance from natural protected areas increases.

Table 14. Distance from natural protected areas and corresponding costs used in the Reclassify tool

Distance (m)	Cost
0 – 100	5
100 – 200	4
200 – 300	3
300 – 500	2
> 500	1

8. Maximise distance to major river streams

Different distance classes and their corresponding costs are given in Table 15. The cost decreases as the distance from natural protected areas increases.

Table 15. Distance from major rivers and corresponding costs used in the Reclassify tool

Distance class (m)	Cost
0 – 100	5
100 – 200	4
200 – 350	3
350 – 500	2
> 500	1

9. Maximise distance to surface waters – dams and ponds

Distance from surface waters – dams and ponds – and corresponding costs are given in Table 16. The cost decreases as the distance from natural protected areas increases.

Table 16. Distance from surface waters – dams and ponds and corresponding costs used in the Reclassify tool

Distance class (m)	Cost
0 – 100	5
100 – 200	4
200 – 350	3
350 – 500	2
> 500	1

10. Maximise distance to ground waters

Distance from ground water and corresponding costs are given in Table 17. The cost decreases as the distance from ground water areas increases.

Table 17. Distance from ground waters – dams and ponds and corresponding costs used in the Reclassify tool

Distance class (m)	Cost
0 – 150	5
150 – 250	4
250 – 350	3
350 – 500	2
> 500	1

11. <u>Prioritise arable, grazing, forest and built-up land</u>

The costs assigned to different types of land use and land cover are given in Table 18. The highest priority is given to protecting agricultural/crop lands, grasslands and residential areas. These land use types are assigned the highest cost of 5. The highest costs are also assigned to commercial areas and water bodies and woodland.

Table 18. Land use / land cover types and their corresponding costs used in the Reclassify tool

Land use / Land cover	Cost
OS – Open Space	2
LI – Light Industrial	2
Closed shrubland	2
Open shrubland	2
GI – General Industrial	3
RSU – Residential Suburban	4
C-3 – General Commercial	4
CIV – Civic and Community	4
Sparse forest	4
RU – Residential Urban	5
R-1 – Single Family Residential	5
R-2 – Single Family Residential	5
CBD – Central Business District	5
C-1 – Local Centre	5
R – Recreation	5
MXD-G – Mixed Zone General	5
MXD-C – Mixed Zone Commercial	5
iA-1- Intensive Agricultural	5
eA-2 – Extensive Agricultural	5
Woodland	5
Open grassland	5
Cropland	5
Water body	5
Settlement	5
Buildings	5

12. *<u>Maximise distance to residential areas to reduce air pollution</u>*

Distance from residential areas and corresponding costs for the criterion air pollution are given in Table 19. The cost decreases as distance from residential areas increases.

Table 19. Distance from residential areas and corresponding costs used in the Reclassify tool

Distance class (m)	Cost
0 – 100	5
100 – 200	4
200 – 300	3
300 – 500	2
> 500	1

13. *<u>Maximise distance to residential areas to reduce noise pollution</u>*

Distance from residential areas and corresponding costs for the criterion noise pollution are given in Table 20. The cost decreases as distance from residential areas increases.

Table 20. Distance from residential areas and corresponding costs used in the Reclassify tool

Distance class (m)	Cost
0 – 25	5
25 – 50	4
50 – 125	3
125 – 250	2
> 250	1

5.1.4 Defining the weights of criteria

The Analytical Hierarchy Process (AHP) was used to define criteria weights for every criterion in each of 3 themes: *economy, environmental and social*. The following tables displays a pairwise comparison preference matrix for each theme. The calculated consistency ratio – CR – for every considered theme is less than *0.10* indicating that a degree of consistency is satisfactory.

AHP for the economic theme

Table 21. Pairwise comparison preference matrix for criteria in the economic theme

Criteria	C1	C2	C3	C4	C5	C6
C1	**1.00**	3.00	2.00	3.00	2.00	2.00
C2	0.33	**1.00**	0.33	3.00	0.50	0.50
C3	0.50	3.00	**1.00**	3.00	0.50	0.50
C4	0.33	0.33	0.33	**1.00**	0.50	0.50
C5	0.50	2.00	2.00	2.00	**1.00**	2.00
C6	0.50	2.00	2.00	2.00	0.50	**1.00**

Table 22. Criteria within the economic theme and calculated weights through AHP

Criteria No.	Criteria	Weight
C1	Minimise unfavourable topographic conditions – slope of the terrain	0.29
C2	Minimise a number of by-pass crossings with roads with high priority	0.10
C3	Minimise a number of by-pass crossings with rivers with high-order drainage	0.16
C4	Maximise distance to flooding areas	0.07
C5	Maximise geological construction suitability	0.21
C6	Maximise soil construction suitability	0.17

Calculated CR – value: 0.021

AHP for environmental theme

Table 23. Pairwise comparison preference matrix for criteria in the environmental theme

Criteria	C7	C8	C9	C10
C7	**1.00**	0.50	2.00	3.00
C8	2.00	**1.00**	2.00	3.00
C9	0.50	0.50	**1.00**	2.00
C10	0.33	0.33	0.50	**1.00**

Table 24. Criteria within the environmental theme and calculated weights

Criteria No.	Criteria	Weight
C7	Maximise distance to natural protected areas	0.29
C8	Maximise distance to fragile water streams	0.41
C9	Maximise distance to surface waters – dams and ponds	0.19
C10	Maximise distance to ground waters	0.11

Calculated CR – value: 0.026

AHP for social theme

Table 25. Pairwise comparison preference matrix for criteria in the social theme

Criteria	C11	C12	C13
C11	**1.00**	5.00	5.00
C12	0.20	**1.00**	0.50
C13	0.20	2.00	**1.00**

Table 26. Criteria within the social theme and calculated weights

Criteria No.	Criteria	Weight
C11	Prioritise arable, grazing, forest and built-up land	0.70
C12	Maximise distance to residential areas to reduce air pollution	0.12
C13	Maximise distance to residential areas to reduce noise pollution	0.18

Calculated CR – value: 0.047

5.1.5 Combining criteria within each theme

There are 3 defined themes: *economy, environmental* and *social*. Within each, criterion maps were combined using the *Weighted Sum* geoprocessing tool. The criterion weights obtained through *AHP* were entered into the *Weighted Sum* tool.

5.1.6 Defining the weights of themes

Each theme favours corresponding criteria that belong to it. For example, the economy theme gives more consideration to 6 criteria classified under it. To combine the themes themselves, the weight for each theme needs to be defined. Again the Analytical Hierarchy Process *AHP* is used here. The preference of one theme (criteria) over another is shown in a pairwise comparison matrix by expert choice evaluation.

The following tables present the pairwise comparison preference matrix in which each theme is compared to the remaining two. The calculated CR was less than *0.10* indicating that a degree of consistency is satisfactory.

As seen from the calculated weights, depending on which theme is preferable, every theme receives twice as much weight than the remaining two themes. For example, when the economic theme is preferable, it receives 50% weight while the remaining two, environmental and social, each receive a weight of 25%.

In addition, the fourth group was also defined, in which every theme receives an equal weight of 33.33%.

The calculated consistency ratio – CR – for every obtained combination is *0.00* indicating *perfect* consistency.

AHP when the economic theme is the most favourable

Table 27. Pairwise comparison preference matrix when the economic theme is the most favourable

Criteria	T1	T2	T3
T1	**1.00**	2.00	2.00
T2	0.50	**1.00**	1.00
T3	0.50	1.00	**1.00**

Table 28. Calculated weights by AHP when the economic theme is the most favourable

Criteria No.	Criteria (Theme)	Weight
T1	Economic	0.50
T2	Environmental	0.25
T3	Social	0.25

Calculated CR – value: 0,00

AHP when the environmental theme is the most favourable

Table 29. Pairwise comparison preference matrix when the environmental theme is the most favourable

Criteria	T1	T2	T3
T1	**1.00**	0.50	1.00
T2	0.50	**1.00**	2.00
T3	0.50	1.00	**1.00**

Table 30. Calculated weights by AHP when the environmental theme is the most favourable

Criteria No.	Criteria (Theme)	Weight
T1	Economic	0.25
T2	Environmental	0.50
T3	Social	0.25

Calculated CR – value: 0.00

AHP when the social theme is the most favourable

Table 31. Pairwise comparison preference matrix when the social theme is the most favourable

Criteria	T1	T2	T3
T1	**1.00**	1.00	0.50
T2	0.50	**1.00**	0.50
T3	0.50	1.00	**1.00**

Table 32. Calculated weights by AHP when the social theme is the most favourable

Criteria No.	Criteria (Theme)	Weight
T1	Economic	0.25
T2	Environmental	0.25
T3	Social	0.50

Calculated CR – value: 0.00

AHP when each theme is equally important

Table 33. Pairwise comparison preference matrix when each theme has equal preference

Criteria	T1	T2	T3
T1	**1.00**	1.00	1.00
T2	1.00	**1.00**	1.00
T3	1.00	1.00	**1.00**

Table 34. Calculated weights by AHP when each theme has equal preference

Criteria No.	Criteria (Theme)	Weights
T1	Economic	0.33
T2	Environmental	0.33
T3	Social	0.33

Calculated CR – value: 0.00

5.1.7 Combining each theme

The *Weighted Overlay* geoprocessing tool is used to combine the themes. The weights for each theme defined using the Analytical Hierarchy Process (AHP) were entered into this geoprocessing tool. Thus, 4 routes were produced.

5.1.8 Using the ArcGIS ModelBuilder

Once the data had been pre-processed, they were ready to be used further in all geoprocessing tools described in the "Model description" section. Conducting all of these steps manually would be greatly time-consuming, especially when testing a range of different criterion weights. Thus, it was decided to use ModelBuilder, instead. The ModelBuilder interface in ArcGIS 10.5 is more of a flowchart scheme that guides the user to visually lay out a certain task. Once the model has been built, it can be run again with different parameters allowing the user to obtain results quickly. Not only does the model save time, it also ensures that errors are avoided. The model flowchart that was built and used in this process is shown in Figure 25. The main steps in ModelBuilder are numbered and explained.

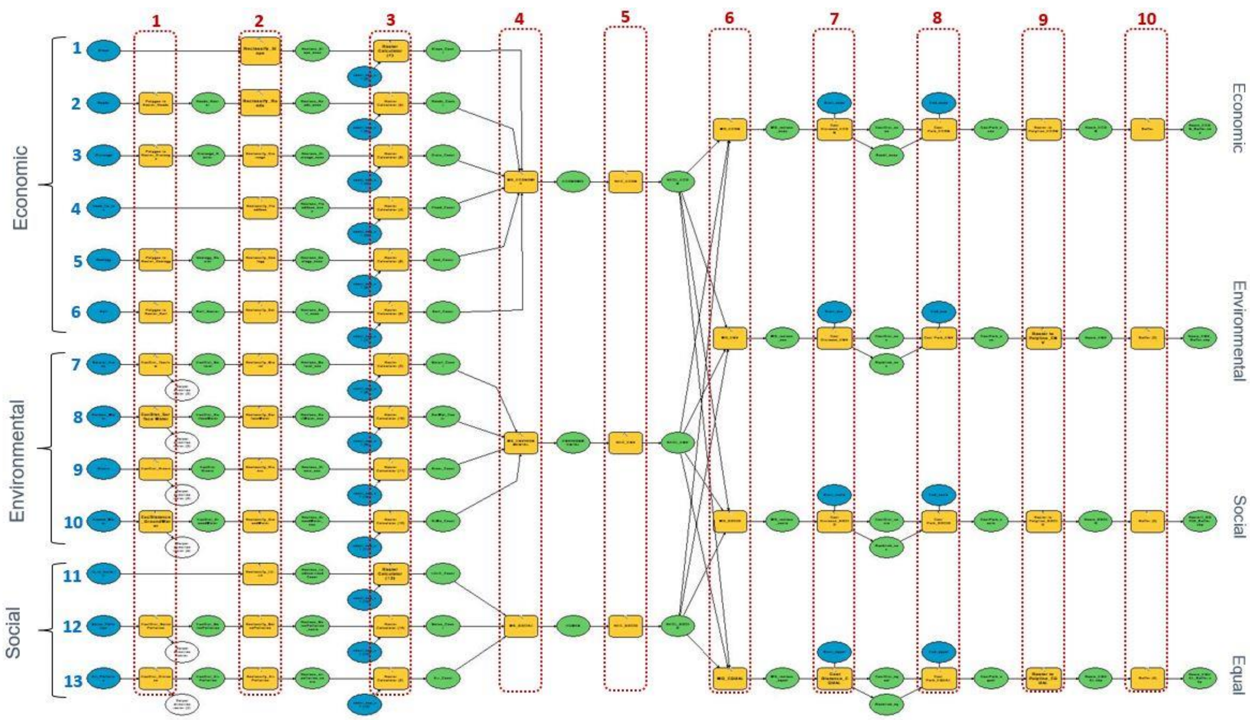

Figure 25. Flowchart of the Tlokweng model

The input data in the model are numbered. 13 datasets are used representing different criteria used in this analysis.

<u>*Step 1 – pre-processing data*</u>

1- In this step, no geoprocessing tool was used on the raster dataset representing slope
2- A polygon dataset representing the existing road network was converted to a raster dataset (the *Polygon to Raster* geoprocessing tool was used)
3- A polygon dataset representing the drainage order was converted to a raster dataset (the *Polygon to Raster* geoprocessing tool was used)

4- In this step, no geoprocessing tool was used on the polygon dataset representing flooding areas
5- A polygon dataset representing geology type was converted to a raster dataset (the *Polygon to Raster* geoprocessing tool was used)
6- A polygon dataset representing soil type was converted to a raster dataset (the *Polygon to Raster* geoprocessing tool was used)
7- The distance was found for the polygon dataset representing areas with parks, flora and fauna (the *Euclidian distance* geoprocessing tool was used)
8- The distance was found for the polygon dataset representing major river streams (the *Euclidian distance* geoprocessing tool was used)
9- The distance was found for the polygon dataset representing surface waters – dams and ponds (the *Euclidian distance* geoprocessing tool was used)
10- The distance was found for the polygon dataset representing underground waters (the *Euclidian distance* geoprocessing tool was used)
11- In this step, no geoprocessing tool was used on the raster dataset representing land use/land cover data
12- The distance was found for the polygon dataset representing residential areas and areas of future urban expansion (the *Euclidian distance* geoprocessing tool was used)
13- The distance was found for the polygon dataset representing residential areas and areas of future urban expansion (the *Euclidian distance* geoprocessing tool was used)

Step 2 – criteria constraint
Finding areas where alternatives are possible by applying constraint criteria. This was done using the *Raster Calculator* geoprocessing tool.

Step 3 – criteria standardisation
Criteria standardisation was performed using the *Reclassification* geoprocessing tool.

Step 4 – combining criteria within each theme
The *Weighted Sum* geoprocessing tool was used to combine criteria within each theme.

Step 5 – reclassification of each theme
Step 4 gives raster datasets for each theme with a floating point within each cell. In this step, the *Reclassification* geoprocessing tool was used to obtain raster datasets with integer values that could be used in the next step.

Step 6 – combining themes
In order to combine themes, the *Weighted Overlay* geoprocessing tool was applied.

Step 7 – finding the least accumulative cost distance
The *Cost Distance* geoprocessing tool was used to calculate the least accumulative cost distance for each cell from the least-cost source (start point)

Step 8 – finding the least-cost path
The *Cost Path* geoprocessing tool was used to find the least-cost path (by-pass alignment) from source to destination (end point).

Step 9 – converting least-cost path to polyline
The *Raster to polyline* geoprocessing tool was used to convert the cost path to a polyline feature dataset. This was necessary for later analysis.

Step 10 – finding a certain buffer area on the obtained polylines by-passes
For further analysis it was necessary to find a road reserve area of 60 metres, thus the *Buffer* geoprocessing tool with the distance of 30 metres applied in this step.

5.2 Using the model in the case study

The model constructed using ArcGIS ModelBuilder is applied to the case study for the Tlokweng Planning Area. The model produces 4 different by-pass road alignments: *economic, environmental, social* and *equal* The points between which by-pass road alignments should be created are based on an official document – *"Revision of the Tlokweng Development plan (2001-2025)",* (GIS Plan, 2018). These points are coded as point shapefiles. According to the plan, two by-passes should be considered: one running through the south part of the Tlokweng study area and one running through its northern part. The coded points are shown in Figure 26. Alignment for the southern by-pass should run between the green points shown on the map. The northern by-pass road alignment should be between the blue points running north-south from Tlokweng city centre.

One can notice that the location of the southern point for the northern by-pass routes differs in regard to the position presented in the mentioned document – *"Revision of the Tlokweng Development plan (2001-2025)"*. After consultation it was decided to move this point further from its initial location which was at the border with the Republic of South Africa. One of the reasons is the future location of the economic zone (see Figure 18). It is expected that trucks travelling towards and from the Republic of South Africa will use this zone; thus the location of the mentioned point will enable them to use the economic zone on their journey.

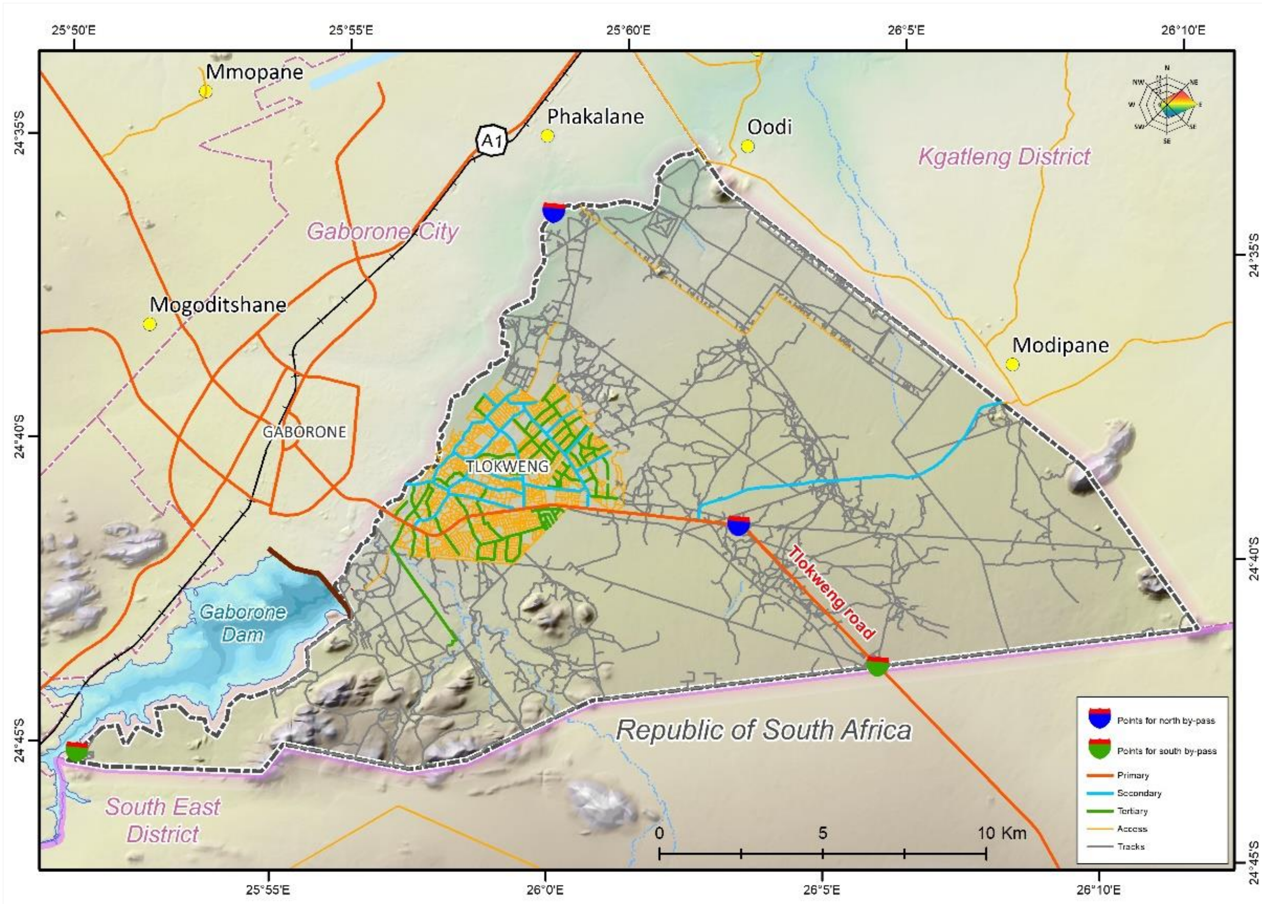

Figure 26. Determined locations between which northern and southern by-pass alignment should be defined

Road alignments produced in this way are presented as a raster dataset. Then the *Raster to Polyline* geoprocessing tool is used to convert each alignment to polyline format.

The next step was to use the *Buffer* geoprocessing tool to create a 30-metre buffer for every alignment. This was done in respect to the decision presented in *"Revision of the Tlokweng Development plan (2001-2025)"* where it is mentioned that a road reserve area of 60 metres in width is necessary for the design of the road in question (GIS Plan, 2018).

5.2.1 Road class for a by-pass

To perform a by-pass comparison it was necessary to define a suitable road class. According to the road-design manual for Botswana, design standards are for rural and urban roads considered separately (Ministry of Transport & Communications, 2014). There are 6 classes for the former. A proposed by-pass belongs to road class 2 – *R2*, *single carriageway*. This consists of two lanes plus shoulders, with turning lanes at intersections as needed. In general, road class – R2 provides the highest level of service at the greatest speed for the longest uninterrupted distance, with the maximum degree of access control. These roads are to be designed to the highest standards as they link cities, towns and centres of economic importance with each other and to regional roads. Their main function is to provide mobility, meaning that they carry almost exclusively long distance traffic. They will have partial-to-full access control (Ministry of Transport & Communications, 2014).

Cross-sections standards for this type are shown in Figure 27 below. Figure 28 shows the road profile for this road class. As can be seen, the lane width is 3.7 metres with shoulder width of 2.5 metres. The maximum road reserve width for dual carriageways is 90 metres.

Road Class	R1 Freeway Dual Single	R2 Freeway Dual Single	R3 Single	R4 Single	R5 Single	R6 Single
Road Reserve Width (m)	90	90	70	50	40	15
Green Zone (m)	2 x 5.0	2 x 5.0	2 x 5.0	2 x 5.0	2 x 5.0	
Design Speed[1] (km/h)	120	120	100	80	80 - 60	
Lane Width[2] (m)	3.7	3.7	3.5	3.5	3.35	
Shoulder Width: (m)						
Surfaced[3,4]	2.5	2.5	2.5	1.5	1.5	
Un-surfaced					1.5	
Surfacing:[7]						
Carriageway	S	S	S	S	S/G	S/G
Shoulder	S	S	S	S	S/G	
Camber/Crossfall:[5, 6]						
Carriageway (%)	2.0 - 3.5	2.0 - 3.5	2.0 - 3.5	2.0 - 3.5	2.0 - 3.5	3.0 - 4.0
Shoulder (%)	2.0 - 3.5	2.0 - 3.5	2.0 - 3.5	2.0 - 3.5	2.0 - 3.5	

Figure 27. Rural road cross-section design standards (Ministry of Transport & Communications, 2014)

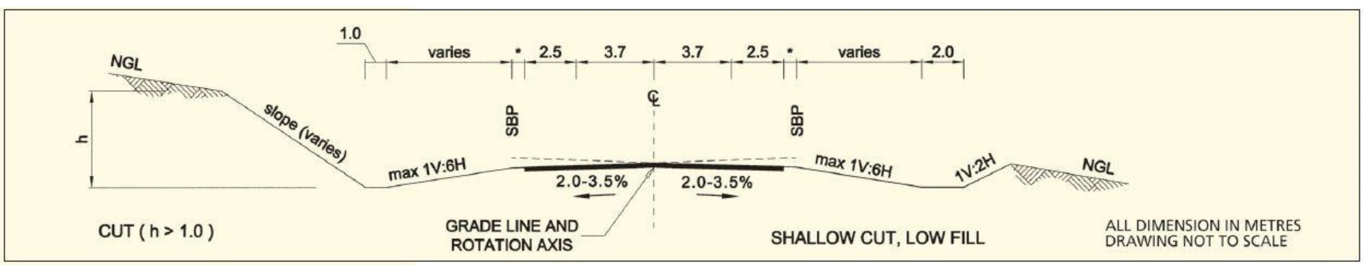

Figure 28. Road profile for class R2 single carriageway (Ministry of Transport & Communications, 2014)

5.3 Model validation

An independent validation matrix was created in order to compare routes and validate the model. It consists of 8 elements, listed below:

C1. Number of agro land plots crossed
C2. Number of objects demolished
C3. Number of crossings with primary, secondary and tertiary roads
C4. Number of crossings with rivers with 5th, 6th, 7th and 8th stream order
C5. Earth works cut and fill (m3)
C6. Total amount of asphalt and rocks used to build a by-pass (m3)
C7. Length of tunnel (metres)
C8. Length of bridge (metres)

To find results for - C1. Number of agro lands plots crossed, C2. Number of objects demolished, C3. Number of crossings with primary, secondary and tertiary roads and C4. Number of crossings with 5th, 6th, 7th and 8th river stream orders the following geoprocessing tools were used for each produced road by-pass alignment:

- The *Buffer* geoprocessing tool with a distance of 30 metres was used to create a polygon around every by-pass alignment. This gives a road reserve area of 60 metres.
- The *Select Layer by Location* geoprocessing tool was used to find the number of objects for each of the elements - C1, C2, C3 and C4.

C5. Earth works, cut and fill

To compute the total earthwork (cut and fill) for each GIS-produced by-pass road alignment including the alignment proposed within the *"Revision of the Tlokweng Development plan (2001-2025)"* document, several steps were performed. The steps are classified into two groups.

The steps belonging to the first group are completed using the ArcGIS software package. They are as follows:

- The *Interpolate Shape* geoprocessing tool was applied to all by-pass alignments to obtain the correct elevation. Input surface was Digital Elevation Model – DEM – for the Tlokweng study area.
- The *Create TIN* geoprocessing tool was used to create a triangulated irregular network – TIN – dataset. Input contours every 2 metres were used as an input feature class in this step.
- The *TIN Triangle* geoprocessing tool was applied to export the TIN dataset to polygon features where each triangle is described with the correct slope.
- The *Buffer* geoprocessing tool was used to create 50-metre buffer zones (polygons) around each by-pass alignment.
- The *Edit TIN* geoprocessing tool was used to clip the TIN Triangle using polygons created from previous steps (see Figure 29).

Figure 29. Example of created TIN datasets as a polygon shapefile imported into Novapoint (example shows part of a by-pass for an environmental theme)

The above-mentioned steps help to obtain the terrain for every by-pass alignment. This way the terrain area was substantially reduced and ready for use in the steps within the second group. Here the main idea was to apply the *Novapoint* software package which is used for detailed road design. This software can create 3D road models using different road profiles, computed cut-and-fill works and materials needed to build the road, design of vertical and horizontal alignments, etc… It works in connection with the AutoCAD software package. The following steps were performed in this stage:

- A clipped TIN Triangle in the form of a shapefile and every road alignment was imported into Novapoint
- The road profile was defined in Novapoint according to the road design manual for Botswana (Ministry of Transport & Communications, 2014).
- The maximum slope of 8.0% for by-passes was chosen in accordance with the road design manual for Botswana (Ministry of Transport & Communications, 2014). Using Novapoint the vertical by-pass alignment was adjusted for stretches where the slope is higher than 8.0%. Every by-pass alignment was thoroughly checked and where it was noticed that the slope of vertical alignment was higher than 8.0% it was adjusted further.
- Next, the number of kilometres of tunnels and bridges necessary for every alignment was calculated. This was based on the following two rules (Roh et al., 2008):
    - If the difference of embankment height to the vertical alignment is more than 20 metres then the bridge should be constructed (see Figure 30).
    - If the cutting height is more than 30 metres then a tunnel should be constructed (see Figure 30).

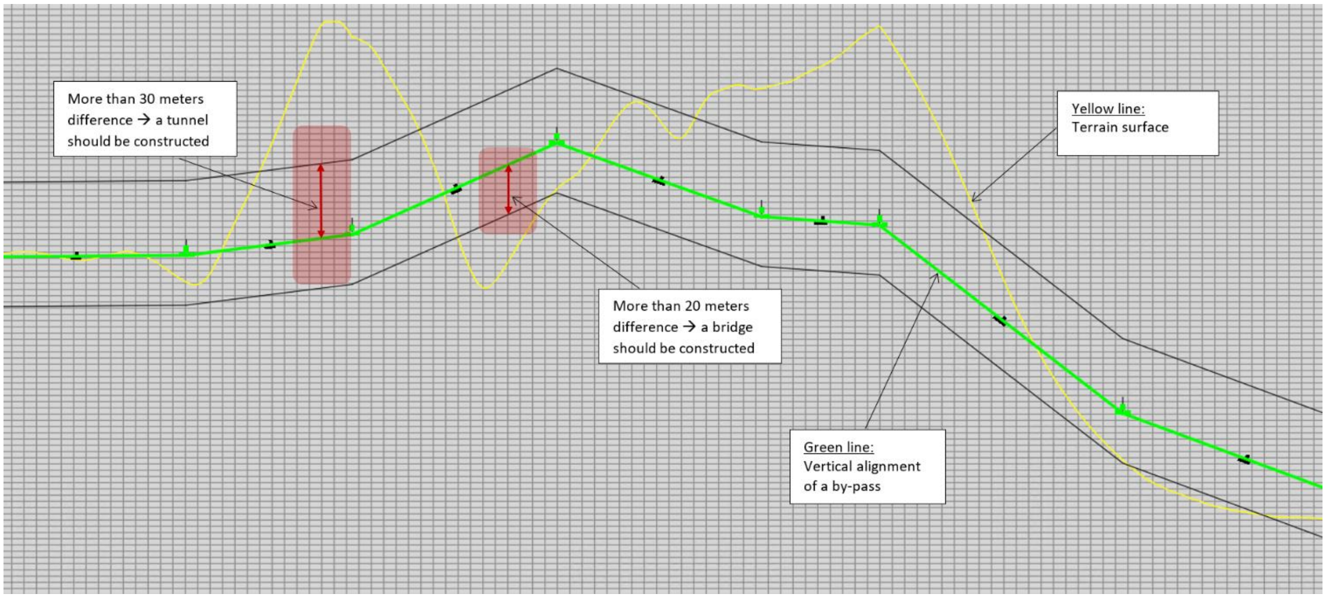

Figure 30. Rules for deciding if a bridge and/or a tunnel is needed to be constructed (vertical alignment shown in green is a by-pass alignment presented in "Revision of the Tlokweng Development plan (2001-2025)"*)*

- Besides cut-and-fill works, the total amount of materials in terms of asphalt and rocks necessary to build every by-pass was also computed

One has to bear in mind that the cut-and-fill results obtained this way represent more ***approximate values***. As mentioned, the GIS model gives the optimal alignment in respect to economic, environmental and social characteristics in the second part of road-planning process in Botswana (feasibility study) (see Figure 2). Therefore, detailed road geometry is not considered and thus the estimated cut-and-fill works are approximate.

Figure 31 shows an example of a cut-and-fill diagram produced in Novapoint. It shows a cut-and-fill diagram for a south by-pass road alignment for an economic routes. Only part of the south by-pass alignment within the economic theme is shown – in this case the stretch from 5 130 to 9 720 metres.

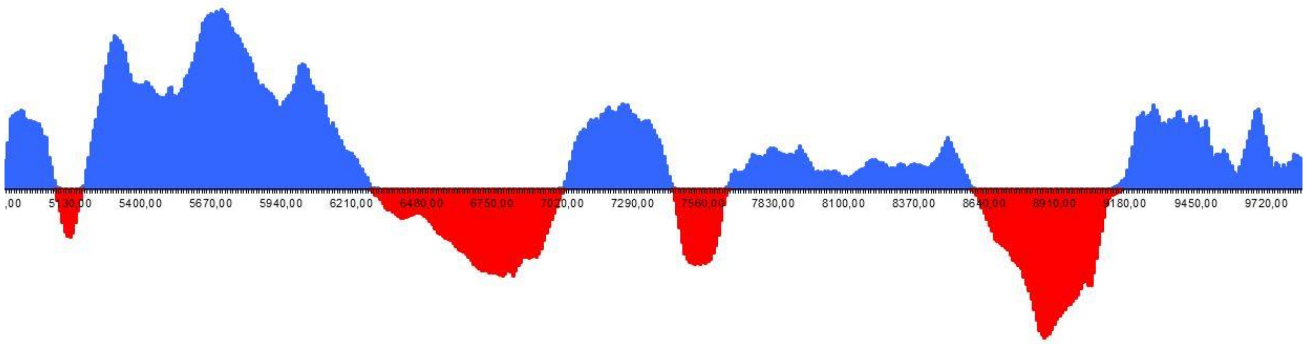

Figure 31. Earth works – cut-and-fill diagram for part of the economic south alignment (red-shaded areas represent fill; blue-shaded areas represent cut)

C6. Length of the tunnels, expressed in km
This was computed using Novapoint.

C7. Length of the bridges, expressed in km
This was computed using Novapoint.

C8. Ranking of produced by-pass road alignments
Ranking of alignments was carried out in the following 2 steps:

- The first step includes applying the Analytical Hierarchy Process (AHP) to determine the weights of each of the 8 above-mentioned elements. The particular focus when determining preferences in a pairwise comparison preference matrix is given to the *agro lands* as the Tlokweng community have shown special interest in protecting that land use type. The pairwise comparison preference matrix and computed weights are shown in Table 35. The calculated consistency ratio – CR – is 0.003 indicating that the condition CR<= 0.10 is satisfied.

Table 35. Pairwise comparison preference matrix for validation matrix elements

Elements	C1	C2	C3	C4	C5	C6	C7	C8
C1	**1.00**	2.00	2.00	3.00	2.00	2.00	3.00	3.00
C2	0.50	**1.00**	3.00	5.00	0.14	0.20	0.20	0.33
C3	0.50	0.33	**1.00**	3.00	0.33	0.50	1.00	1.00
C4	0.33	0.20	0.33	**1.00**	0.50	0.50	1.00	1.00
C5	0.50	7.00	3.00	2.00	**1.00**	0.50	3.00	3.00
C6	0.50	5.00	2.00	2.00	2.00	**1.00**	3.00	3.00
C7	0.33	5,00	1.00	1.00	0.33	0.33	**1.00**	1.00
C8	0.33	3.00	1.00	1.00	0.33	0.33	1.00	**1.00**

Table 36. Calculated weights for validation matrix elements by applying AHP

Elements	Description	Weight
C1	Number of agro lands plots crossed	0.22
C2	Number of objects demolished	0.10
C3	Number of crossings with primary, secondary and tertiary roads	0.08
C4	Number of crossings with rivers (5^{th}, 6^{th}, 7^{th} and 8^{th} stream order)	0.06
C5	Earth works cut and fill (m3)	0.18
C6	Total amount of asphalt and rocks (m3)	0.19
C7	Length of tunnel (metres)	0.09
C8	Length of bridge (metres)	0.08

Calculated CR – value: 0.003

- Ranking of routes was conducted using the *DEFINITE* decision-making software package for a finite set of alternatives (Janssen and Herwijnen, 1994). If alternative solutions can be identified within the problem in question, then *DEFINITE* is used to weigh up the alternatives and select the best.

  This software offers different methods for standardising the criteria. Linear scale transformation methods are mostly used and within this group the two procedures most applied are maximum score and score range (Malczewski & Rinner, 2015). To standardise evaluation criteria, *maximum score* was applied. The formula for performing standardisation can be expressed as follows:

$$xij' = 1 - \frac{xij}{xj(\max)}$$

- xij' – is standardised score of the i-th criterion within a group of criteria (j)
- xij – is the raw value of the i-th criterion within a group of criteria (j)
- xj (max) – is the maximum score of the criteria within a group of criteria (j)

DEFINITE offers several methods for ranking solutions: *weighted summation, Electre 2, Regime* and *Evamix*. The *weighted summation* method was applied in this thesis.

5.4 Sensitivity analysis

Conducting sensitivity analyses in the field of spatial multi-criteria analysis is not common practice (Malczewski, 2006; Delgado & Sendra, 2004), partly because it is time-consuming.

The goal of performing sensitivity analysis within multi-criteria analysis in GIS is to explore how small changes in criteria weights affect results. It can be used to investigate in more detail how a model reacts to these changes. In particular, sensitivity analysis can help reduce uncertainty in multi-criteria analyses and check the stability of its outputs (Chen, 2010). Therefore, it can increase the understanding of the relationship between input and output variables (Saltelli et al., 2008).

One of the simplest and most common approaches used is *"One-At-a-Time"(OAT)* or *"One-At-Factor-a-Time"(OFAT)* sensitivity analysis. Here, one factor is changed at a time to see what effects it produces on the output. In general, OAT involves the following steps (Saltelli et al., 2004).

- Changing one input variable while keeping others at their baseline values,
- Returning the changed variable to its baseline value, then repeating the same procedure for every other input

One-At-a-Time OAT sensitivity Analysis approach
The following important points are related to setting up the sensitivity analysis:

1. In OAT sensitivity Analysis in this thesis, the *base scenario* represents the criteria weights defined through the Analytical Hierarchy Process (AHP) (see weights defined under "Methodology" section).
2. In every theme, each criterion weight is changed by 1% (*incremental* percentage change - IPC) within the range of -20% to +20% (range percentage change – RPC). The base case scenario represents the case where the percentage change is equal to 0%. Thus, the total number of runs for each criterion is 41. Therefore, the total number of runs in the entire analysis could be expressed as follows:

$$Total\ number\ of\ runs = \sum_{i=1}^{n}\sum_{j=1}^{k}\sum_{m=1}^{h}(m)\,j(i)i$$

- ***n*** *is the total number of themes*
- ***k*** *is the total number of criteria within a theme* ***i***
- ***h*** *is the total number of incremental percentage change (incremental percentage change is 1% within the range of (-20%, +20%)), representing 41 runs for each criterion* ***j***

3. When changing the criterion weight by an *incremental* percentage change IPC within a corresponding theme, the *additivity constraint* applies. This means that the sum of weights for all criteria within a corresponding theme is equal to 1.0 at any percentage change. The additivity constraint at any percentage change for all criteria weights within a theme could be shown as follows:

$$Wi(m) = \sum_{j=1}^{k} Wi(jm) = 1\ ,\ \ m \in (RPCmin, RPCmax), (\mathrm{i}\ = 1 \div 3)$$

- ***Wi(m)*** *is the sum of criteria weight within a theme* ***i*** *(i = 1 – 3) at percentage change* ***m***
- ***j*** *is the total number of criteria within a theme* ***i***
- ***Wi(jm)*** *is the weight of criterion* ***j*** at a percentage change **m** *within a theme* ***i***
- ***RPCmin*** *represents the minimum value of range percentage change – RPC (default is -20%)*
- ***RPCmax*** *represents the maximum value of range percentage change – RPC (default is +20%)*

4. The weight of a criterion in question at any percentage change within a corresponding theme consists of the sum of weight defined through the Analytical Hierarchy Process

(AHP), base case scenario and percentage change in question. This could be written as follows:

$$Wi(j,m) = Wi(j,0) + Wi(j,0) * m, \quad m \in (RPCmin, RPCmax), (\mathrm{i} \ = 1 \div 3)$$

- ***Wi(j, m)*** is the weight *for criterion* ***j*** *for which the weight is changing within a theme* ***i***
- ***Wi(j, 0)*** *is the weight for base case scenario for criterion* ***j*** *for which the weight is changing within a theme* ***i***
- ***m*** *is the percentage change within a theme* ***i***

5. To meet the additivity constraint condition it is necessary to adjust the weights of other criteria that belong to a theme for which the weight of main criterion is changing. That means that other criteria need to be readjusted such as the sum of all criteria within a theme is equal to 1.0. The criteria within each theme are adjusted based on their weights defined for the base case scenario through the Analytical Hierarchy Process (AHP). This could be shown as follows:

$$Wi(Cj,m) = \left(1 - Wi(j,m)\right) * \frac{Wi(Cj,0)}{1 - Wi(j,0)},$$

$$, m \in (RPCmin, RPCmax), (\mathrm{i} \ = 1 \div 3)$$

- ***Wi(Cj, m)*** *is the adjusted weight for criterion* ***j*** *within a theme* ***i*** *at a percentage change* ***m***
- ***Wi(j, m)*** is the weight *for criterion* ***j*** *for which the weight is changing within a theme* ***i***
- ***Wi(Cj, 0)*** *is criterion weight* ***Cj*** *for base case within a theme* ***i***
- ***Wi(j, 0)*** is the base case criterion weight ***j*** *for which the weight is changing within a theme* ***i***

The steps to conduct SA are shown in the flowchart below:

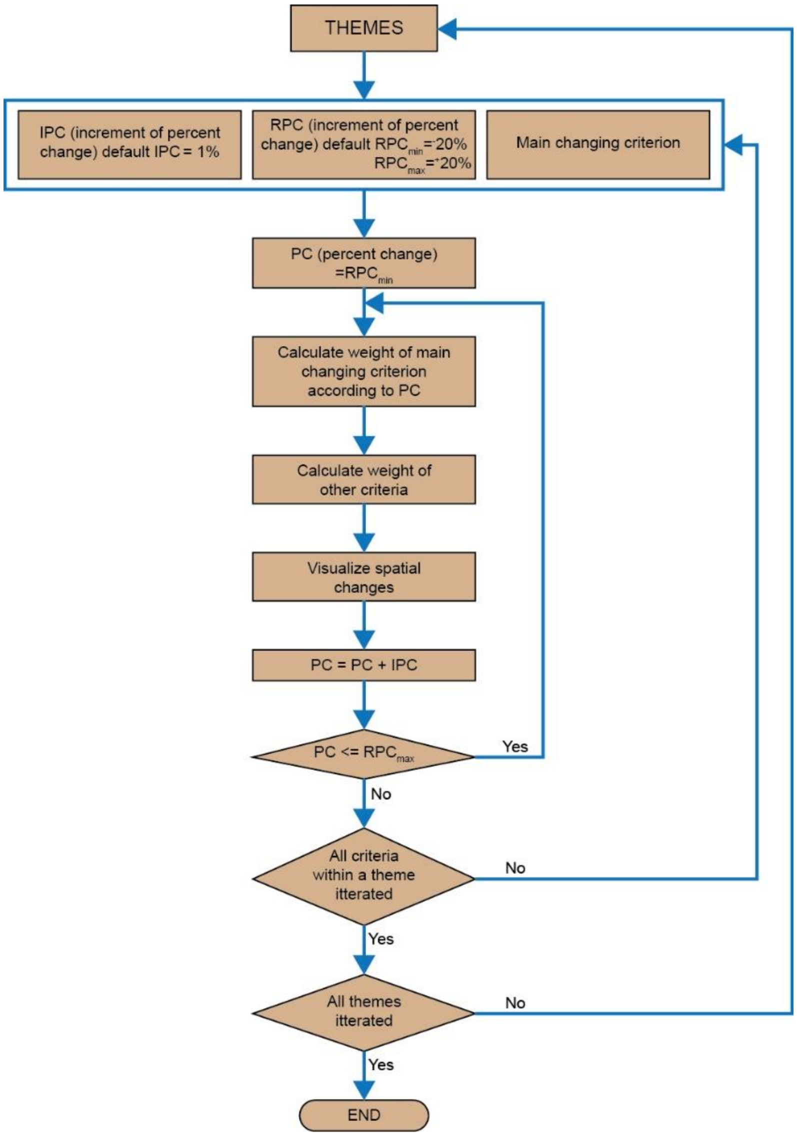

Figure 32. Steps to conduct a sensitivity analysis (adapted from Chen et al., 2010)

Implementing OAT Sensitivity Analysis
The Python programming language is used to perform OAT sensitivity analysis. Python can be connected with ArcGIS through the ArcPy module giving it flexibility and a wide range of possibilities.

A standalone Python script was written that emulates the entire Tlokweng model built in ModelBuilder (see Figure 25). Some of the steps executed by the script are listed below:

- Perform the iterations over every criterion within each theme by changing the criterion weight by 1% in the range of - 20% up to and including + 20%, while at the same time other criteria weights within a corresponding group are readjusted to satisfy the equation for the additivity constraint (*additivity constraint* means the sum of all criteria weights within each theme (group) is 1.00)

- Produce the cost raster datasets and give the total number of cells belonging to each cell with a cost value from 1 to 5
- Create raster datasets showing how many cells have been changed from one cell value to another through every iteration. This should be done for all possible combinations, for example, changing the cell values within the class that has a cost value of 1 (from 1 to 1, from 1 to 2, from 1 to 3, from 1 to 4, from 1 to 5, etc….).
- Export data to Excel and create tables and corresponding charts. In particular, the output result show how many cells for each class value from 1 to 5 are changed and perturbations among the cells.

It is worth mentioning that the script is flexible as it can be adjusted very easily depending on what the main focus is. In particular, one can:

- change criterion weight and theme weights,
- exclude or include new criteria,
- easily adjust and change the *incremental* percentage change – IPC and range percentage change – RPC if necessary (default value for IPC is 1% and for RPC is from -20% up to and including + 20%)

Purpose of OAT sensitivity analysis
Regarding OAT sensitivity analysis in this thesis particular attention is given to:

- *Investigating the robustness of the entire model*

  As each cell within a raster dataset represents a possible alternative, it is important to investigate the robustness of the entire model. Depending on its sensitivity, this can reveal which criteria should be investigated in more detail and if the entire model is "safe" to use in similar analyses.

  The total number of changed cells for the entire Tlokweng Planning area was studied. The changes in cost values for cells (from 1 to 5) in respect to base case scenario were investigated for every criterion. As mentioned above, the total number of iterations per criterion is 41, where a criterion weight is changed by a step of 1% within the range of -20% to +20%.

  In order to conclude if the model is sensitive to criterion weight changes, we start with the *statistical test for one proportion*. Given a sample proportion, $\hat{p}$, and the sample size, n, this statistical test is used to test claims about the true population proportion, p.

  In this test, the null and alternative hypotheses, in respect to the problem in question – determining if the proportion of cells changed is significant – can be stated as follows:

H_0 : The true proportion of cells is unchanged → (p = 0)

H_a : The true proportion of changed cells is higher than 0 → (p > 0)

Under the assumption of normal approximation to binomial distribution (n is large), the Z-score test statistic can be applied for hypothesis testing for proportion. The test statistic, Z, could be written as follows:

$$Z = \frac{\hat{p} - p_0}{\sqrt{\frac{p_0(1 - p_0)}{n}}}$$

- *$\hat{p}$ is the estimate of the true proportion*
- *p_0 is the hypothesised proportion*
- *n is the sample size*

Likewise for the above test for proportion, the distributions of count X (the number of events or frequency) could also be used in such tests (Lyman & Longnecker, 2001). The number X is the binomial random variable with parameters n and p. Thus, test statistic, Z, for frequencies could be written as follows:

$$Z = \frac{X - np_0}{\sqrt{np_0(1 - p_0)}}$$

- *X is the frequency estimate*
- *p_0 is the hypothesised proportion*
- *n is the sample size*

<u>In the test for frequency in respect to the problem in question – namely determining if total number of cells changed is significant – the null and alternative hypotheses can be stated as follows:</u>

H0 : The total number of cells is unchanged → (X = 0)

Ha : The total number of changed cells is higher than 0 → (X > 0)

It can be seen that the null hypothesis claims that the total number of cells remains unchanged. Thus, the test statistic for frequency cannot be directly used in the form shown above, since the hypothesised proportion, p_0, is equal to 0. The modified form of this test statistic must be applied instead when the test is related to <u>*zero proportion*</u>.

In his article, Jonathan R. Bradley presents the statistical test for zero proportion (Bradley & Farnsworth, 2003). He postulates that due to misclassification some instances may seem to occur even when it is not possible. He presented two tests that can be used to investigate such problems – *the frequentist* and *Bayesian tests*. Even though his studies are in the field of medicine, this approach can be used by different practitioners.

The frequentist test is presented below. In this statistical test it was proposed to include ***misclassification rates*** in a statistical test for proportion. The modified test statistic, *Z*, is thus expressed as follows:

$$Z = \frac{X - np_+}{\sqrt{np_+(1 - p_+)}}$$

- *X is the estimate of frequency*
- *p_+ is the misclassification rate*
- *n is the sample size*

Further, by re-writing the above formula, the critical value of X can be expressed as follows:

$$X_c = np_+ + z_\alpha \sqrt{np_+(1 - p_+)}$$

- *X_c is the critical value of the estimate of frequency*
- *$\alpha = P(Z \geq z_\alpha)$ is the level of significance*
- *p_+ is the misclassification rate*
- *n is the sample size*

The suggested value for the misclassification rate, p_+, is within the range of 0,01 and 0.03. If one wants to be more restrictive it is proposed to lower the value of p_+.

If the number of events within the sample is designated a feature of X_s then the conclusion can be drawn by comparing the value of X_s with the critical value of x_c.

If $X_s \geq x_c$ then the count is too large compared to the number expected from misclassification alone. Thus, the null hypothesis is rejected.

In contrast, if $X_s < x_c$, then there is not sufficient evidence to reject the null hypothesis.

In respect to drawing conclusions regarding the changed cells, it seems reasonable to use the above-described approach. The total number of cells with a raster dataset (with cell size of 5 by 5 metres) is over 11 million while the total number of changed cells is substantially less. Also, the null hypothesis claims that the number of changed cells is 0, thus all conditions for applying the test for zero proportion are met.

In respect to the number of changed cells, the critical value of the number of changed cells Xc is calculated by applying the above-mentioned formula. The assumed misclassification rate, p_+, is 0.01 and the significance level, α, is 0.05.

- *visualise the spatial change of evaluation results*

  Based on the above approach, if the model confirms sensitivity to some criterion weight changes, then it is useful to visualise where the changing of cells occurs in the space. This gives the spatial pattern of criterion weight sensitivity identifying those cells within a raster dataset that have some degree of uncertainty. The spatial pattern is only shown for those criteria where the significant number of changed cells is confirmed using the statistical test for zero proportion.

The entire MCE-GIS model used in this thesis is shown in Figure 33.

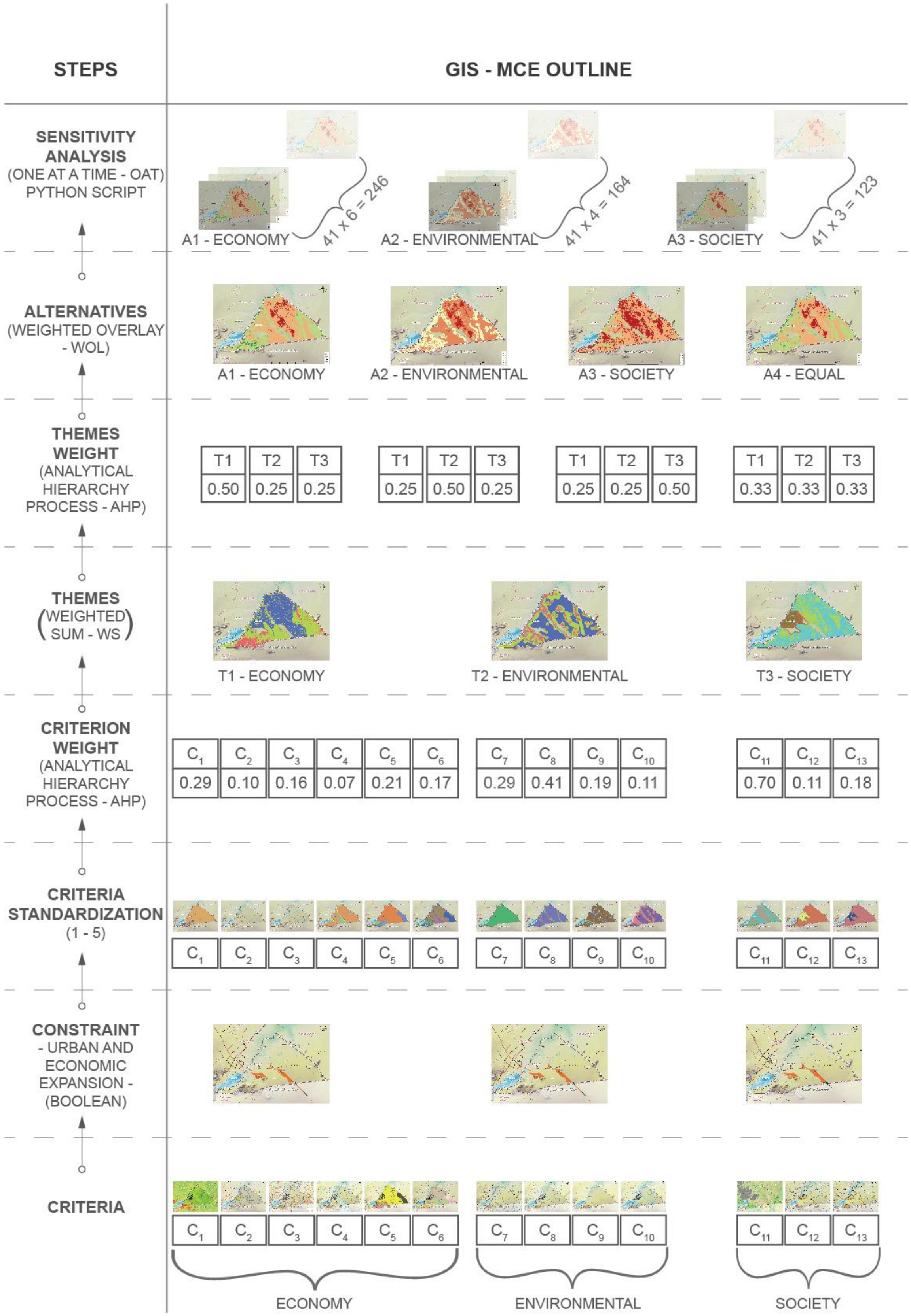

Figure 33. GIS-MCE approach

6 Results and discussion

This section presents the main results as follows:

- Obtained by-pass road alignments as the final results from running ModelBuilder (step 10 – least-cost path within ModelBuilder, see Figure 25).
- Comparing by-pass alignments
- Sensitivity analysis

All other ancillary results obtained through running ModelBuilder such as *Euclidian Distance* performed on different input layers, *Cost Distance* raster datasets, etc… are given in Appendix II.

6.1 By-pass alignments obtained by ModelBuilder

There are 4 considered solutions: *economic*, *environmental*, *social* and *equal themes*. Raster datasets that show the costs on a scale from 1 to 5 together with proposed northern and southern by-pass alignments are shown in the following figures.

Proposed by-pass road alignment when the economic theme is preferable

The cost raster dataset when the economic theme is the most preferable is shown in Figure 34. The highest costs are located in the southwestern part of the study area where hilly areas are mostly situated. Areas with the highest costs are also seen along the major river systems, around the areas with the highest stream order.

These areas should be avoided when an economic by-pass alignment is considered. Proposed by-pass alignments for southern and northern parts of the Tlokweng study area where there is an economic preference are shaded dark blue. It is clear that the alignments avoid areas with the highest costs. For example, the southern by-pass alignment avoids areas with high slopes as this would increase construction costs.

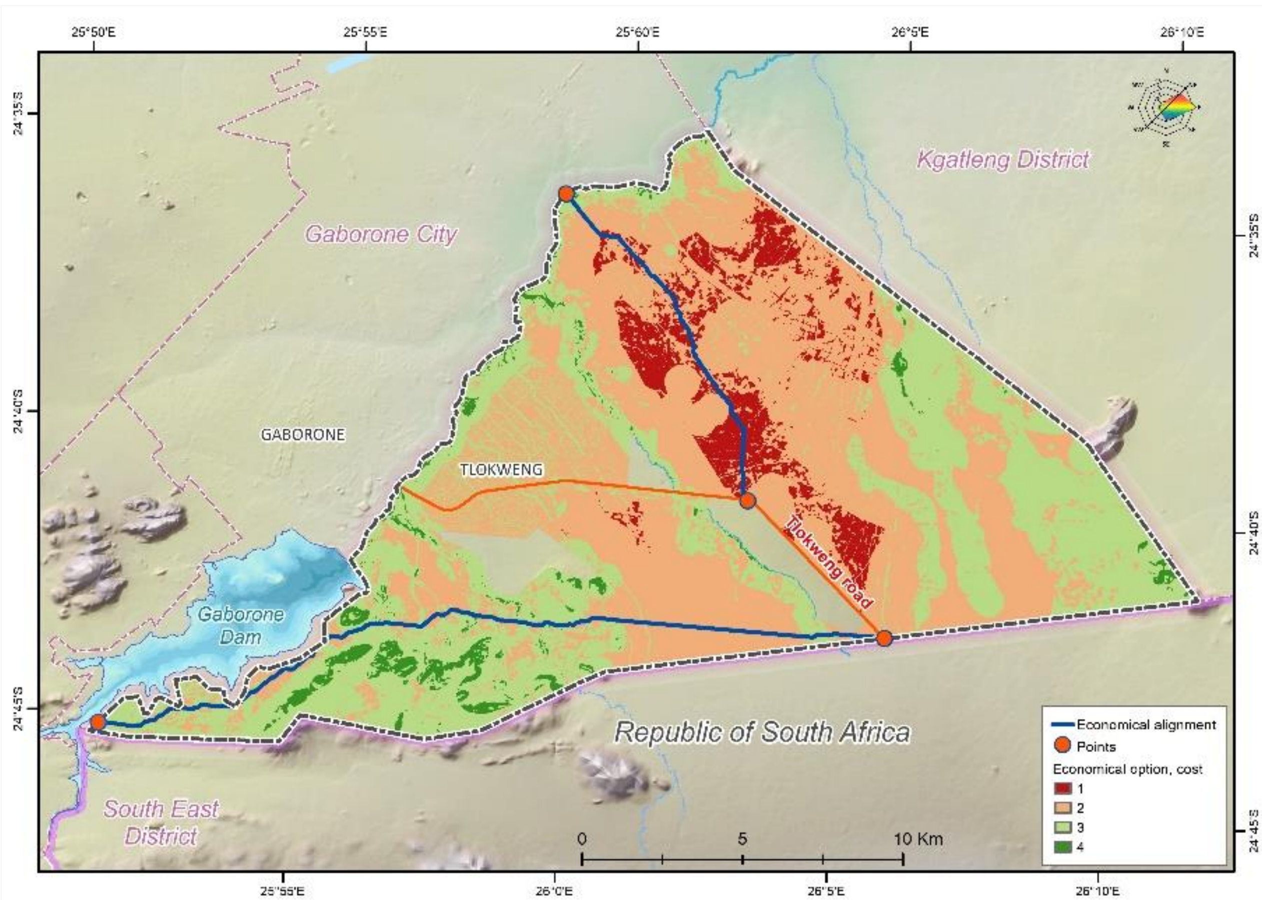

Figure 34. Cost raster dataset when the economic theme is the most preferable

Proposed by-pass road alignment when the environmental theme is preferable

The cost raster dataset when the environmental theme is the most preferable is shown in Figure 35 below. The highest costs are where dams and ponds are located in southwestern and northern areas where the protection of natural areas is given high preference. Also there are high costs along the major rivers as they are protected within the environmental theme.

These areas should be avoided when an environmental by-pass alignment is considered. Proposed by-pass alignments in the southern and northern parts of the Tlokweng study area with an environmental preference are shaded dark green. It is clear that the GIS algorithm proposes that the alignments go through the least-cost areas with respect to the environment. The alignment in the south does not avoid hilly areas even though construction costs would be high, but at the same time environmental costs are lowest.

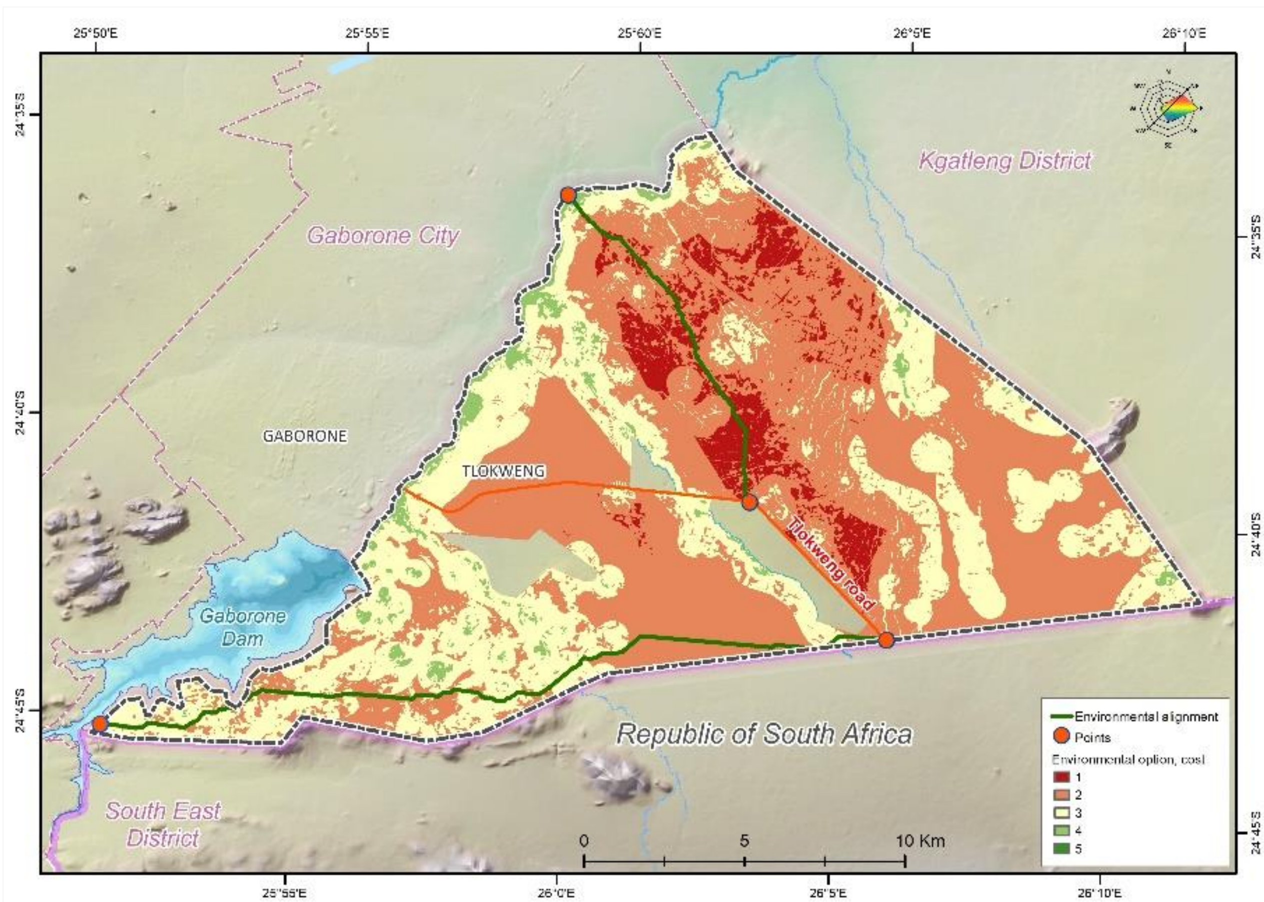

Figure 35. Cost raster dataset when the environmental theme is the most preferable

Proposed by-pass road alignment when the social theme is preferable

The cost raster dataset when the social theme is the most preferable is shown in Figure 36. The areas with high costs are located within the urban Tlokweng area and areas where the agricultural land is located.

When a social by-pass alignment is considered these areas should be avoided. Proposed by-pass alignments for the south and northern parts of the Tlokweng study area with a social preference are shaded dark yellow. It is clear that the GIS algorithm proposes that the alignments go through the least-costs areas with respect to social costs. For example, the alignment in the northern part of the study area goes through the areas where the costs of the cells within the equal raster dataset are lowest and equal 2.

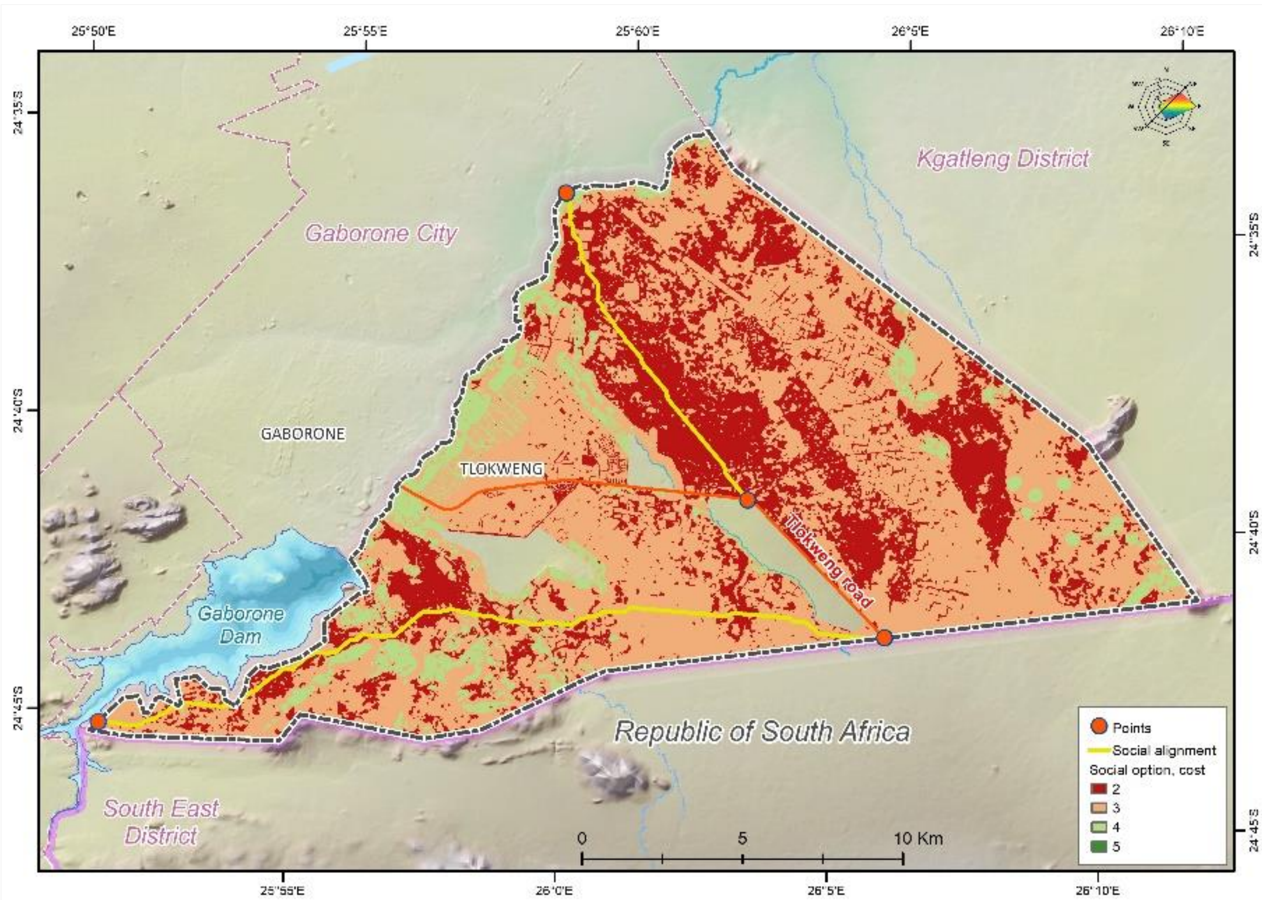

Figure 36. Cost raster dataset when the social theme is the most preferable

Proposed by-pass road alignment when all themes are equally preferable
The cost raster dataset when the equal theme is the most preferable is shown in Figure 37. Here economic, environmental and social themes receive equal weight. Thus, if the areas with highest costs overlap for the three main themes, the equal solution will show the height costs for these areas too.

It is noticeable that the highest cost areas, shaded dark green, appear in the southwest part of the Tlokweng study area and west of the urban area. The proposed by-pass alignments for the south and northern parts of the Tlokweng study area with equal preference are shaded pink. The by-pass on the south avoids high cost zones including mountainous areas.

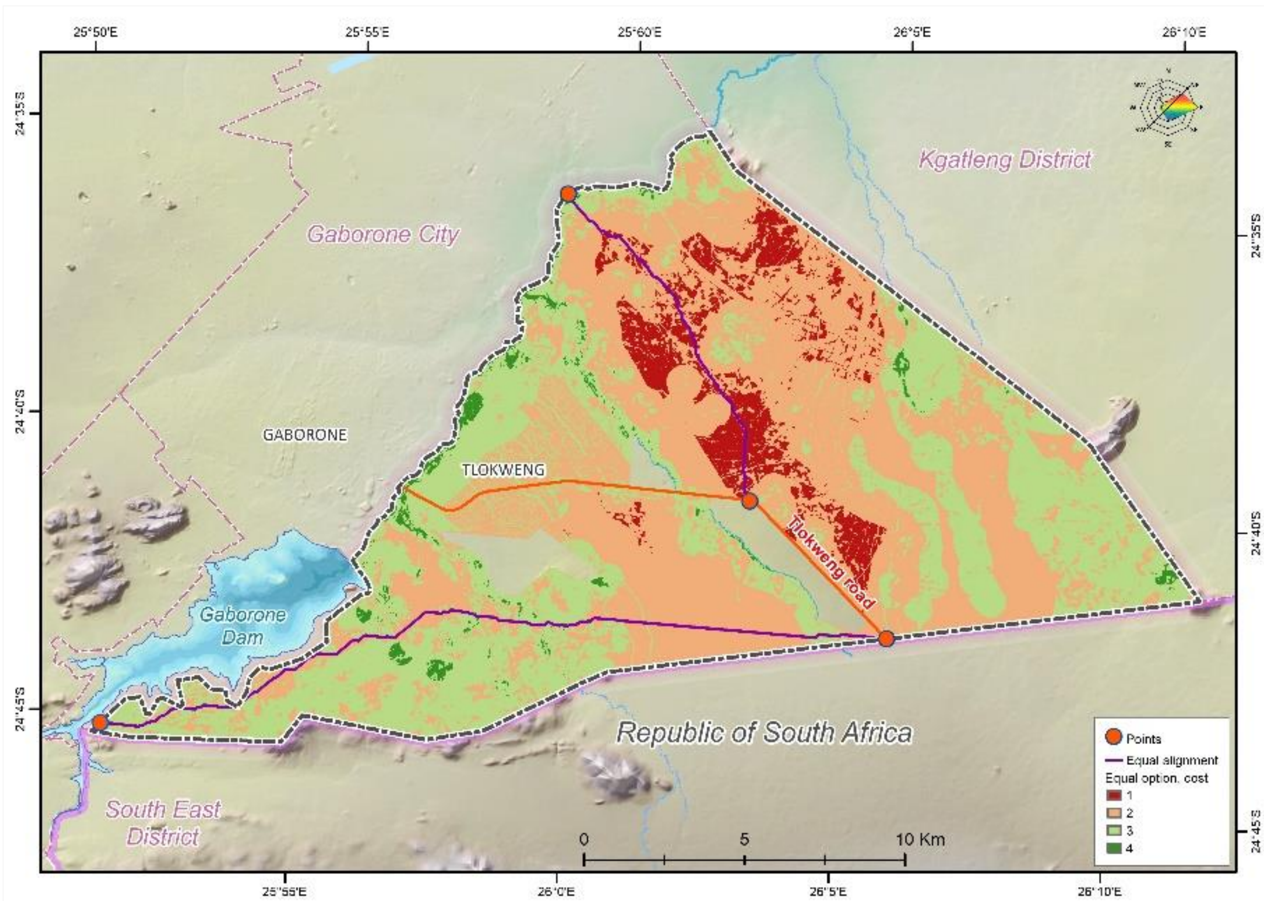

Figure 37. Cost raster dataset when the equal theme is the most preferable

All GIS-produced by-pass alignments are shown in Figure 38. The by-pass alignments proposed by the Tlokweng Development Plan are also presented. Regarding the alignments that run through the southern part of the Tlokweng study area we can see that the economic, social and equal solutions are very similar. These alignments mostly overlap; however, the environmental and planned options differs significantly.

On the other hand, when it comes to proposed alignments on the north, one can see that the economic, environmental and social routes follow more or less the same alignment. Social and planned by-pass alignments stand out as different.

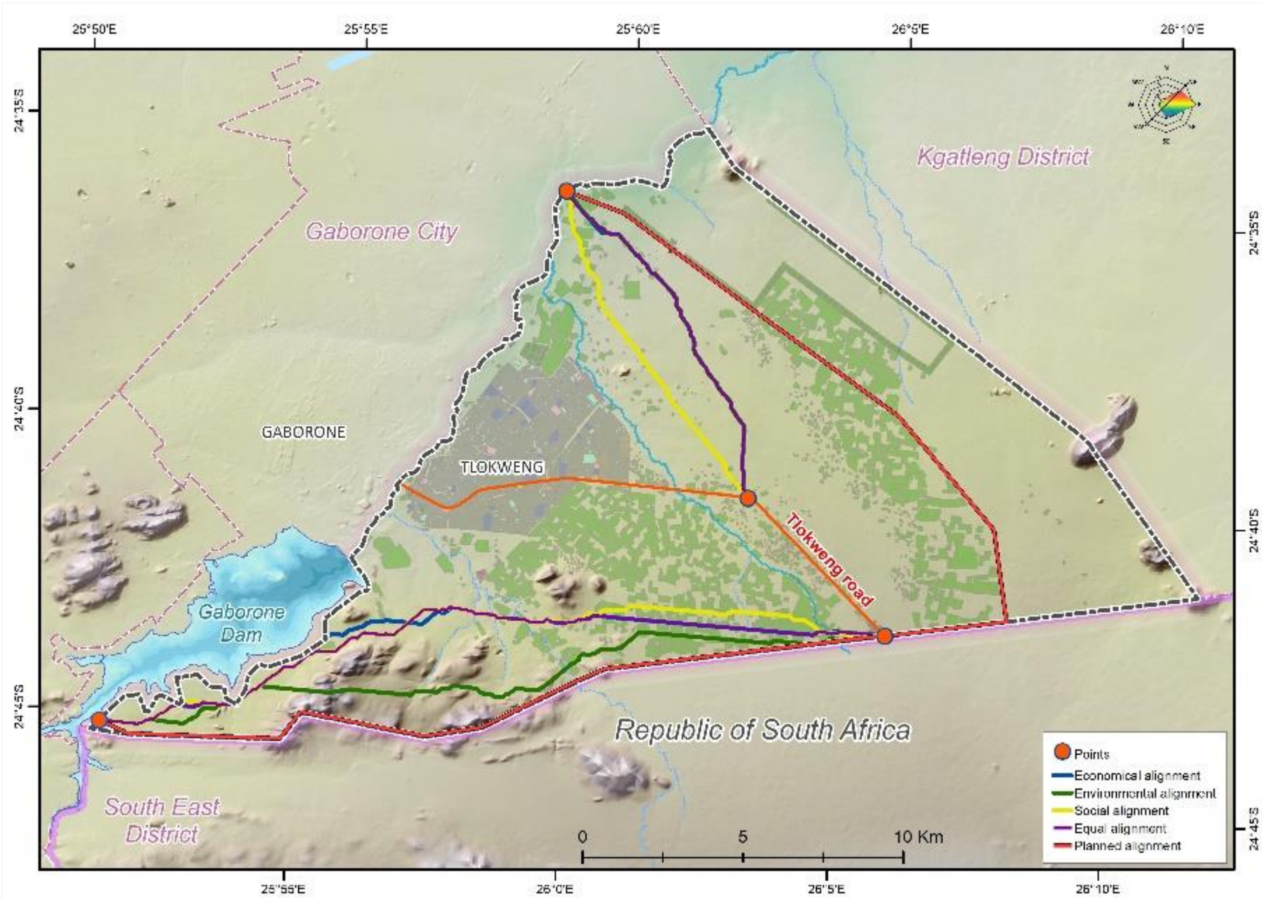

Figure 38. By-pass road alignments within the Tlokweng study area

6.2 Ranking by-pass alignments

The summary of results is presented in Table 37. The results regarding north and south by-pass alignments are summed together. Thus, Table 37 shows the computed values of 8 element independent matrix as a summation of both the north and south by-pass for every considered route.

Table 37. Summary table: calculated values for each route

	Economy	Environmental	Social	Equal	Planned
C1. Number of agro land plots crossed	**39**	**31**	**27**	**32**	**37**
C2. Number of objects demolished	**40**	**32**	**30**	**38**	**69**
C3. Number of crossings with primary, secondary and tertiary roads					
– Primary	1	1	1	1	1
– Secondary	1	1	1	1	1
– Tertiary	0	0	1	1	0
– Total number of crossings with roads	**2**	**2**	**3**	**3**	**2**
C4. Number of crossings with rivers with 5th, 6th, 7th and 8th stream order					
– 5th	6	4	6	6	8
– 6th	2	2	2	2	4
– 7th	0	0	0	0	0
– 8th	0	0	0	0	0
– Total number of crossings with rivers	**8**	**6**	**8**	**8**	**12**
C5. Earth works cut and fill (m3)					
- Earth works – cut (m3)	743050	1200924	752264	776145	4798152
- Earth works – fill (m3)	51820	1779275	28372	66052	1724404
– Total earth works – cut + fill (m3)	**794870**	**2980199**	**780636**	**842197**	**6522557**
C6. Total amount of asphalt and rocks used to build a by-pass (m3)					
– Total amount of asphalt (m3)	29090	29052	28927	29042	37180
– Total amount of rocks (m3)	75179	75220	74897	75196	96266
– Total amount of asphalt and rocks (m3)	**104269**	**104272**	**103824**	**104238**	**133446**
C7. Total length of tunnel (metres)	**0**	**970**	**0**	**0**	**2100**
C8. Total length of bridge (metres)	**0**	**0**	**0**	**0**	**700**

As mentioned, the *DEFINITE* software package was used to rank obtained solutions. Standardisation of the 8 elements of the independent matrix was performed by *maximum score linear scale transformation*. The results are given in Appendix III for each element. Defining the elements' weights was carried out through AHP (see Table 36). The *weighted summation* was applied to rank the alternatives.

Figure 39 shows the how routes differ from each other. It clearly shows the difference between 4 road alignments produced by applying multi-criteria approach and a proposed alignment as a result of the approach in which the local community is widely involved in a final decision.
Regarding the 4 routes produced by GIS, the results show that ***Social alignment*** is the best followed by Equal. *"Number of agro land plots crossed"* mostly contributes to the difference between social and equal routes. Further, it is revealed that element 5 – *"Total amount of earth works (cut and fill)"* contributes most to the total score for 3 alignments: social, equal and economy. Also, for these 3 alignments a similar distribution of elements C5, C6, C7 and C8 is presented in the total score.

The results show that ***Planned alignment*** departs from the mathematical models and methods used in this thesis. The main reason is that a different approach was used while making the planned route. In this case the bottom-up approach was used in which most decisions are highly driven by public involvement, i.e. by representatives of the local community.

Thus, the two mentioned approaches are significantly different. This also reveals the importance of an early involvement of all parties in such projects. In that case, differences in results between MCE-GIS-produced alignments and the planned alignment will not probably be shown to such a great extent.

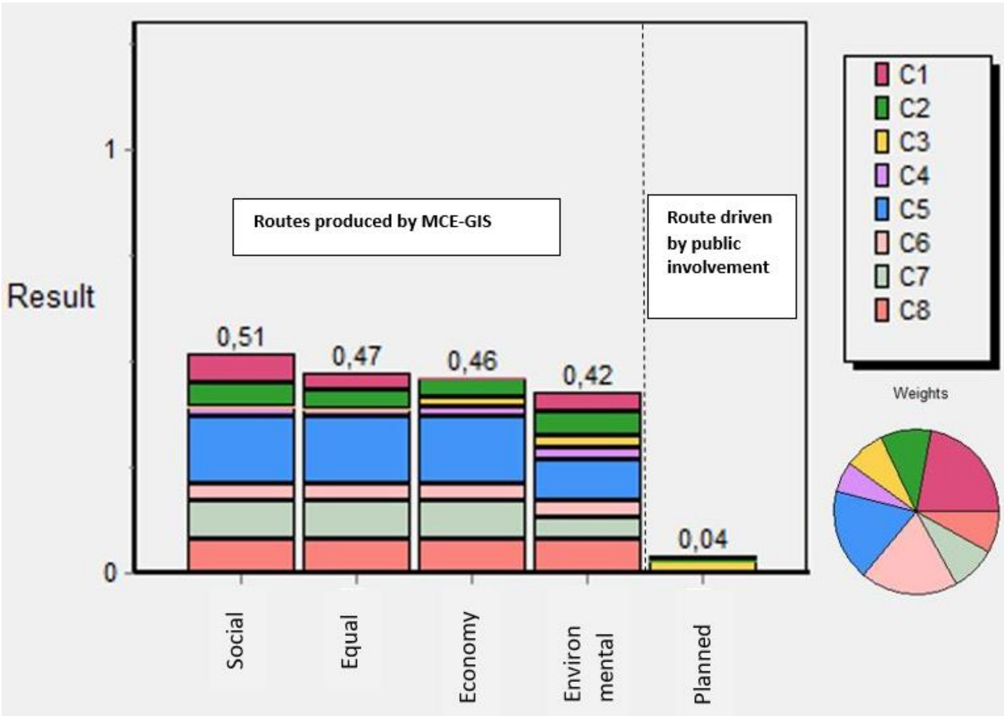

Figure 39. Ranking and total scores using weighted summation

Table 38. Elements of independent matrix used in routes evaluation

C1	Number of agro land plots crossed
C2	Number of objects demolished
C3	Number of crossings with primary, secondary and tertiary roads
C4	Number of crossings with rivers (5th, 6th, 7th and 8th stream order)
C5	Total amount of earth works – cut and fill (m3)
C6	Total amount of asphalt and rocks (m3)
C7	Length of tunnel (metres)
C8	Length of bridge (metres)

Assessment of weights is always subjective; thus different experts and groups will have different perspectives. From the perspective of what society prefers, one can say that mostly weights should be assigned to elements C1 and C2. On the other hand, from the perspective of costs one would probably assign the most weight to elements C7 and C8. *DEFINTE* also offers the possibility to closely investigate the relationships between different perspectives and ranking of the solutions. This is completed so that every element of the matrix gets a 50% weighting while others are assigned the remaining 50% equally distributed. This is shown in Figure 40.

For most perspectives of elements – C1, C2, C5, C6, C7 and C8 – ***social alignment*** scores the best. For most of the mentioned perspectives the social alignment is closely followed by ***economic alignment*** with a difference of 0.01. This is seen for elements – C5, C6, C7 and C8. Regarding perspectives for elements C3 and C4 the ***environmental alignment*** scores the best.

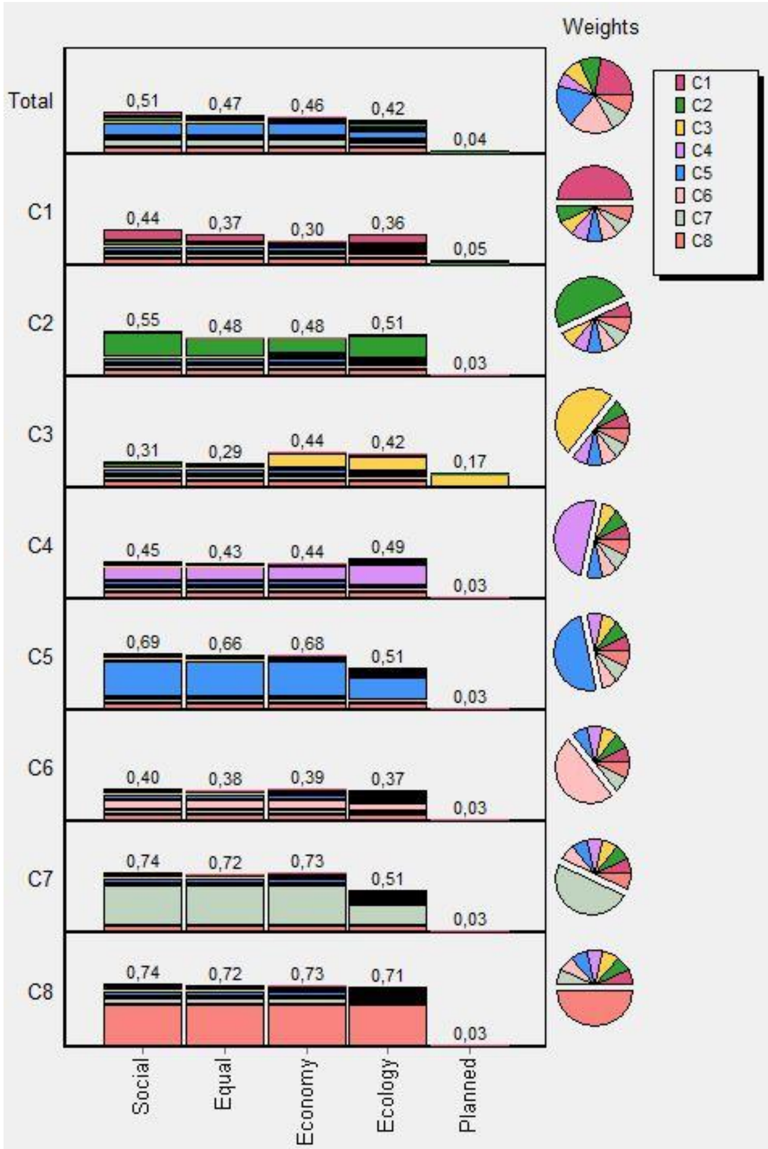

Figure 40. Total scores of the alignments using different perspectives on elements weights

6.3 Sensitivity analysis

Regarding sensitivity analysis, the results are presented in 2 parts. As mentioned before, the main focus of conducting the sensitivity analysis is to:

- check the robustness of the entire model
- visualise the spatial change of evaluation results

The obtained results and descriptions are given follow below.

6.3.1 Robustness of the entire model

To test the robustness for the entire model a closer investigation for the total number of changed cells for every iteration was conducted. table 39 gives more insight into cell behaviour, that is perturbations that happen among different cells class value. Table 39 refers to criterion 1 – "*Minimise unfavourable topographic conditions – slope of the terrain*". All possible combinations for different cell cost values are given. For example, the number of cells that do not change at all through iterations is given for cells belonging to a cost value of 2 (column 22); the number of cells that change from a cost value of 2 to a cost value of 3 is given in column 23, and so on… Column *"TC"* gives the total changes in the number of cells for every iteration.

Tables with these results for other criteria are shown in Appendix III. In the same appendix there are tables showing how the criterion weight changes through every iteration, the number of cells belonging to cell cost value as well each cost class and the computed percentage change.

The statistical test for zero proportion was applied to identify the criteria affecting the entire model sensitivity. To calculate the critical value of Xc with a significance level of 0.05 the following formula applies:

$$X_c = np_+ + z_\alpha \sqrt{np_+(1-p_+)}$$

- *X_c is the critical value of the estimate of frequency*
- *$\alpha = P(Z \geq z_\alpha)$ is the level of significance (for significance level of 0.05, z_α is equal to 1.645)*
- *p_+ is the misclassification rate (the value of 0.01 is used in this analysis)*
- *n is the sample size (the total number of cells within a raster dataset is 11 343 425)*

The calculated critical value, x_c, is 113 986. The total number of changed cells for every iteration for every criterion is compared to the calculated critical value. If the critical value, xc, is less than the total number of changed cells, then the null hypothesis is rejected in favour of the alternative hypothesis – the total number of changed cells is higher than 0.
Table 40 shows the results from this analysis. The red-shaded cells show the iteration, which is the percentage change of criterion weight where the null hypothesis is rejected. For example, it can be seen that the total number of changed cells (the entire model starts to be sensitive) for criterion 1 – "*Minimise unfavourable topographic conditions – slope of the terrain*" – starts when the change of the base case weight is -8%.

Furthermore, based on these results, the 13 criteria can be ranked in accordance when sensitivity starts to be noticeable; that is, ranking of criteria from most to least sensitive. Here it is assumed that the more sensitive criteria occur where the significant change in the total number of cells happens closer to the base case scenario (0% change). The ranking of criteria in respect to sensitivity is given in Table 41 based on the results from Table 40. It can be seen that the most sensitive is criterion 11 – *"Prioritise arable, grazing, forest and built-up land (Land Use / Land Cover)*" while the least is criterion 3 – *"Minimise a number of by-pass crossings with rivers with high-order drainage".*

Table 39. Cell cost changes in raster dataset when the weight of criterion C1 – "Minimise unfavourable topographic conditions – slope of the terrain" changes

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
-20	774151	0	0	0	0	0	6069386	70479	0	0	0	12210	4123044	8917	0	0	0	98704	186534	0	0	0	0	0	0	190310
-19	774151	0	0	0	0	0	6069386	70479	0	0	0	12198	4123056	8917	0	0	0	98603	186635	0	0	0	0	0	0	190197
-18	774151	0	0	0	0	0	6077952	61913	0	0	0	11567	4123742	8862	0	0	0	98517	186721	0	0	0	0	0	0	180859
-17	774151	0	0	0	0	0	6077952	61913	0	0	0	11567	4123871	8733	0	0	0	98517	186721	0	0	0	0	0	0	180730
-16	774151	0	0	0	0	0	6077952	61913	0	0	0	11567	4123871	8733	0	0	0	98517	186721	0	0	0	0	0	0	180730
-15	774151	0	0	0	0	0	6079669	60196	0	0	0	10176	4125262	8733	0	0	0	98489	186749	0	0	0	0	0	0	177594
-14	774151	0	0	0	0	0	6079669	60196	0	0	0	8695	4126743	8733	0	0	0	89095	196143	0	0	0	0	0	0	166719
-13	774151	0	0	0	0	0	6079669	60196	0	0	0	8446	4126992	8733	0	0	0	89095	196143	0	0	0	0	0	0	166470
-12	774151	0	0	0	0	0	6110719	29146	0	0	0	8446	4128138	7587	0	0	0	89022	196216	0	0	0	0	0	0	134201
-11	774151	0	0	0	0	0	6110719	29146	0	0	0	8446	4128138	7587	0	0	0	89022	196216	0	0	0	0	0	0	134201
-10	774151	0	0	0	0	0	6122986	16879	0	0	0	8356	4128228	7587	0	0	0	89022	196216	0	0	0	0	0	0	121844
-9	774151	0	0	0	0	0	6122986	16879	0	0	0	8356	4128228	7587	0	0	0	89022	196216	0	0	0	0	0	0	121844
-8	774151	0	0	0	0	0	6122986	16879	0	0	0	8356	4128228	7587	0	0	0	89022	196216	0	0	0	0	0	0	121844
-7	774151	0	0	0	0	0	6137763	2102	0	0	0	74	4143993	104	0	0	0	16	285222	0	0	0	0	0	0	2296
-6	774151	0	0	0	0	0	6137763	2102	0	0	0	74	4143993	104	0	0	0	16	285222	0	0	0	0	0	0	2296
-5	774151	0	0	0	0	0	6137756	2109	0	0	0	74	4143993	104	0	0	0	16	285222	0	0	0	0	0	0	2303
-4	774151	0	0	0	0	0	6138001	1864	0	0	0	72	4144099	0	0	0	0	15	285223	0	0	0	0	0	0	1951
-3	774151	0	0	0	0	0	6137994	1871	0	0	0	67	4144104	0	0	0	0	15	285223	0	0	0	0	0	0	1953
-2	774151	0	0	0	0	0	6139865	0	0	0	0	67	4144104	0	0	0	0	3	285235	0	0	0	0	0	0	70
-1	774151	0	0	0	0	0	6139865	0	0	0	0	67	4144104	0	0	0	0	3	285235	0	0	0	0	0	0	70
0	**774151**	**0**	**0**	**0**	**0**	**0**	**6139865**	**0**	**0**	**0**	**0**	**0**	**4144171**	**0**	**0**	**0**	**0**	**0**	**285238**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
1	774151	0	0	0	0	0	6139668	197	0	0	0	0	4144111	60	0	0	0	0	285238	0	0	0	0	0	0	257
2	774151	0	0	0	0	0	6139668	197	0	0	0	0	4144111	60	0	0	0	0	285238	0	0	0	0	0	0	257
3	774151	0	0	0	0	0	6139668	197	0	0	0	654	4143457	60	0	0	0	118	285120	0	0	0	0	0	0	1029
4	774151	0	0	0	0	0	6139668	197	0	0	0	654	4143451	66	0	0	0	4040	281198	0	0	0	0	0	0	4957
5	774151	0	0	0	0	0	6133807	6058	0	0	0	1713	4125387	17071	0	0	0	4040	281198	0	0	0	0	0	0	28882
6	774151	0	0	0	0	0	6133807	6058	0	0	0	1713	4125387	17071	0	0	0	4040	281198	0	0	0	0	0	0	28882
7	774151	0	0	0	0	0	6133807	6058	0	0	0	1713	4125387	17071	0	0	0	4040	281198	0	0	0	0	0	0	28882
8	774151	0	0	0	0	0	6133742	6123	0	0	0	1763	4125336	17072	0	0	0	4362	280876	0	0	0	0	0	0	29320
9	774151	0	0	0	0	0	6133742	6123	0	0	0	1763	4125336	17072	0	0	0	4362	280876	0	0	0	0	0	0	29320
10	774151	0	0	0	0	0	6133742	6123	0	0	0	5865	4120895	17411	0	0	0	4497	280741	0	0	0	0	0	0	33896
11	774151	0	0	0	0	0	6133742	6123	0	0	0	5865	4120895	17411	0	0	0	4497	280741	0	0	0	0	0	0	33896
12	774151	0	0	0	0	0	6133683	6182	0	0	0	5865	4117495	20811	0	0	0	4497	280741	0	0	0	0	0	0	37355
13	774151	0	0	0	0	0	6133683	6182	0	0	0	5865	4117495	20811	0	0	0	4497	280741	0	0	0	0	0	0	37355
14	774151	0	0	0	0	0	6133683	6182	0	0	0	9002	4114336	20833	0	0	0	4728	280510	0	0	0	0	0	0	40745
15	774151	0	0	0	0	0	6133341	6524	0	0	0	9002	4114335	20834	0	0	0	4728	280510	0	0	0	0	0	0	41088
16	774151	0	0	0	0	0	6133341	6524	0	0	0	9002	4114335	20834	0	0	0	4728	280510	0	0	0	0	0	0	41088
17	774151	0	0	0	0	0	6133258	6607	0	0	0	9003	4113779	21389	0	0	0	4728	280510	0	0	0	0	0	0	41727
18	774151	0	0	0	0	0	6126359	13506	0	0	0	13241	4106892	24038	0	0	0	8069	277169	0	0	0	0	0	0	58854
19	774151	0	0	0	0	0	6126359	13506	0	0	0	13241	4106892	24038	0	0	0	8069	277169	0	0	0	0	0	0	58854
20	774151	0	0	0	0	0	6126352	13513	0	0	0	13241	4106892	24038	0	0	0	8069	277169	0	0	0	0	0	0	58861

Table 40. Entire model robustness results

PC	Xc	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
-20	113986	190310	29357	54548	24382	57177	46510	61487	93127	181900	129204	608141	41305	39691
-19	113986	190197	29357	54478	24375	56999	46507	61487	93127	181298	129204	608141	41305	39691
-18	113986	180859	29357	54478	24375	56999	46507	29902	93127	121059	129204	608141	41305	39691
-17	113986	180730	29357	54478	24321	55181	46507	29902	93127	119886	129204	608141	41305	39691
-16	113986	180730	27906	33089	24321	55181	8505	29902	93127	110238	127020	591682	41305	39691
-15	113986	177594	27906	33089	24321	38811	8505	29902	92378	108893	127020	591682	41305	39691
-14	113986	166719	27906	32367	24321	38811	8505	29902	92378	107488	127020	591682	41305	39691
-13	113986	166470	27906	32296	1073	38811	5277	16697	91260	107488	127020	591682	41305	39691
-12	113986	134201	27900	32296	1066	38811	5277	16699	91260	106063	125706	572750	39691	39691
-11	113986	134201	27900	32296	1066	3582	5277	15739	91260	106063	125706	572750	39691	39691
-10	113986	121844	27846	29782	1066	3582	3158	14890	91260	106063	94003	572750	39691	39691
-9	113986	121844	27846	29782	1066	3495	3158	14892	91260	103640	94003	572750	39691	39691
-8	113986	121844	350	29782	435	3495	3158	14890	90315	103640	63382	563530	39691	39691
-7	113986	2296	350	25854	435	2236	3155	12843	90227	84616	63382	563530	39691	39691
-6	113986	2296	350	25854	178	2236	3155	12843	87026	84616	63382	563530	39691	39691
-5	113986	2303	350	856	171	2236	693	12843	87026	22997	57464	563530	39691	39691
-4	113986	1951	350	856	85	2236	693	4260	56405	22997	56405	3321	0	0
-3	113986	1953	350	856	85	39	693	1059	56405	22441	56405	3321	0	0
-2	113986	70	264	450	85	39	273	1059	0	21864	0	3321	0	0
-1	113986	70	264	241	85	39	273	0	0	2	0	0	0	0
0	**113986**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
1	113986	257	16	32	179	101	7	0	2	0	2	39691	0	0
2	113986	257	16	32	172	101	7	0	2	57464	2	39691	0	0
3	113986	1029	16	1876	172	101	27	108984	1542	66583	2	39691	0	0
4	113986	4957	16	1876	172	2173	27	108984	1542	66583	2	41305	0	0
5	113986	28882	720	1876	1824	2173	27	108986	3726	67969	2	41305	0	0
6	113986	28882	720	3412	1824	2313	1494	128564	3726	68818	2	41305	3321	0
7	113986	28882	720	3412	2528	2173	1494	128564	3726	68906	2	41305	3321	0
8	113986	29320	720	4293	2535	25483	22856	128566	3726	68906	2	2169445	3321	0
9	113986	29320	1522	4293	2870	25483	22856	128564	9644	70316	21864	2169445	3321	0
10	113986	33896	1522	4293	2870	55669	22856	221886	9644	87418	21864	2169445	3321	0
11	113986	33896	1522	18630	2870	57307	58866	221886	9644	87418	21864	2169445	3321	0
12	113986	37355	5451	18630	2870	57307	58866	221886	9644	115366	21864	2169445	3321	0
13	113986	37355	5451	18808	2870	65867	58866	221886	10958	115366	21864	2169445	3321	0
14	113986	40745	5451	24647	27634	65867	58866	221886	10958	116804	21864	2169445	3321	0
15	113986	41088	5451	24647	27641	68825	58866	222227	10958	116872	21864	2169445	3321	0
16	113986	41088	7436	153209	27634	68825	59335	222227	10958	122995	23194	2169445	3321	0
17	113986	41727	7436	153209	27634	68825	59335	222227	72577	122995	23194	2169445	3321	0
18	113986	58854	7436	153211	27634	73739	59471	222227	73199	131053	23194	2169445	3321	0
19	113986	58854	7436	153218	27634	73739	59471	222228	73199	131069	23194	2169445	3321	0
20	113986	58861	7614	153211	27634	73739	59471	222228	73199	144274	23194	2169445	3321	0

Table 41. List of 13 criteria and criteria ranking

#	Criteria	Ranking
1	Minimise unfavourable topographic conditions – slope of the terrain	**3**
2	Minimise a number of by-pass crossings with roads with high priority	**--**
3	Minimise a number of by-pass crossings with rivers with high-order drainage	**6**
4	Maximise distance to flooding areas	**--**
5	Maximise geological construction suitability	**--**
6	Maximise soil construction suitability	**--**
7	Maximise distance to natural protected areas	**2**
8	Maximise distance to fragile water streams	**--**
9	Maximise distance to surface waters – dams and ponds	**5**
10	Maximise distance to ground waters	**4**
11	Prioritise arable, grazing, forest and built-up land (Land Use / Land Cover)	**1**
12	Maximise distance to residential areas to reduce air pollution	**--**
13	Maximise distance to residential areas to reduce noise pollution	**--**

6.3.2 Visualisation of the spatial change of evaluation results

Sensitivity results can also be presented spatially. The change in the number of cells and cell perturbations can be identified across the space when a criterion weight changes. Thus it can be confirmed where these changes are occurring in the space and which criterion is most sensitive.

One example is shown here for criterion 1 – *"Minimise unfavourable topographic conditions – slope of the terrain"*. The tables shown in Figure 41 and Figure 42 present a 5 by 5 matrix showing cells that belong to each cost value. The number of cells is shown for the base case scenario (PC = 0%) and for the iteration when the cells changes started to be significant (PC= -8%).

The most-often-occurring cell change is a cost value of 4 switching to 3. The location of this sensitive area is marked in Figure 42. This is in the southwestern part of the study area with hilly terrain.

The spatial changes for every criterion identified as a sensitive (see Table 41) are presented in Appendix IV.

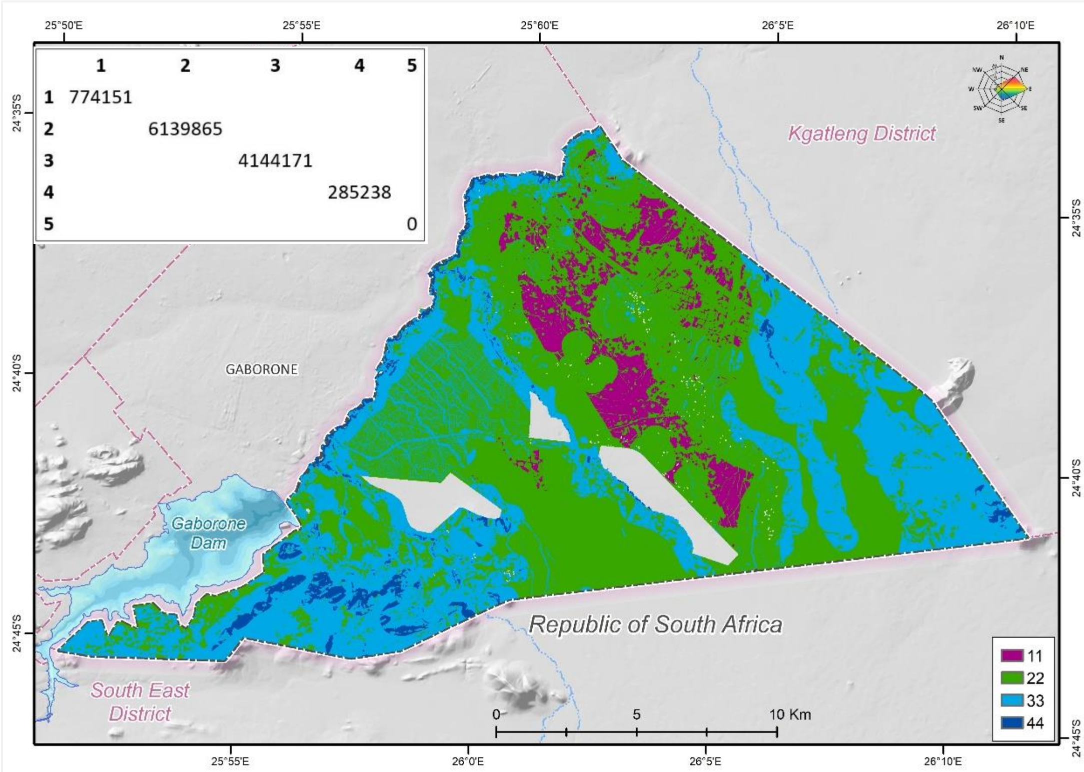

Figure 41. Base case scenario with no changes in criterion 1 weight (PC= 0%)

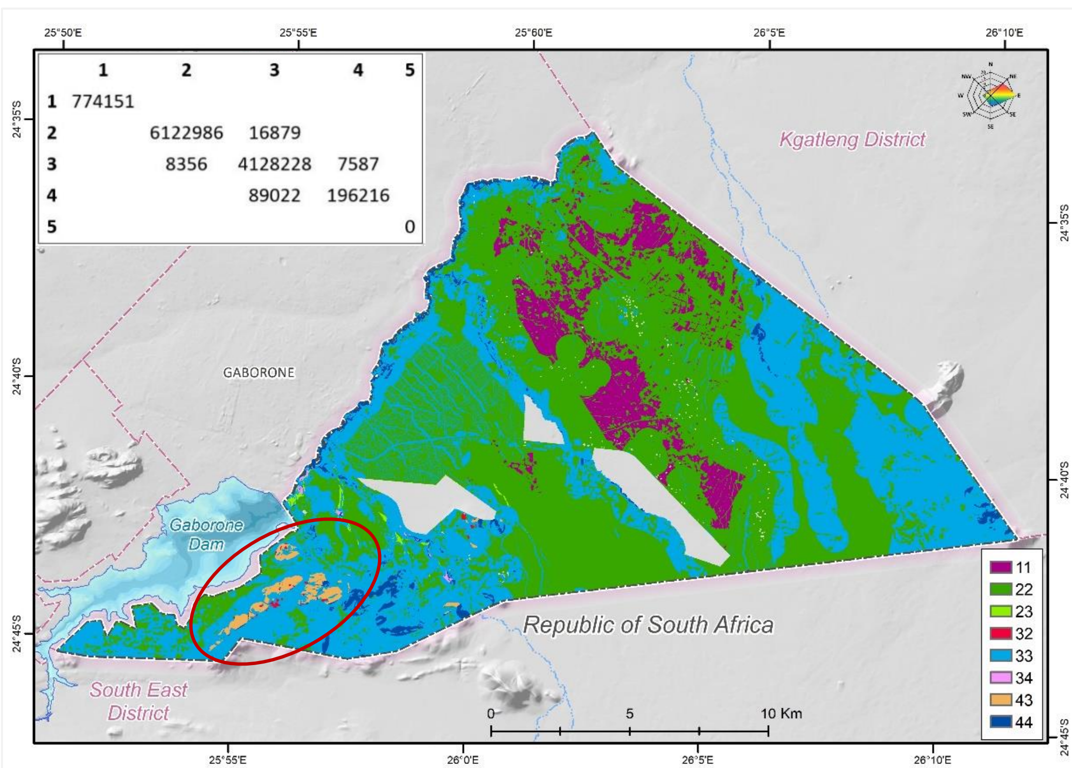

Figure 42. Scenario where the changes in cells started to be significant for criterion 1 (PC= -8%)

Figure 43 shows the areas within the Tlokweng Planning Area recognised as sensitive. These are where significant cell changes occur. The areas are shown for every criterion confirmed as sensitive by applying the test for zero proportion (see Table 41). To increase the robustness of the entire model, the sensitive areas could be further identified in their input datasets. For example, the orange areas (cell values 43, which is the changes from a cell value of 4 to a cell value of 3) shown in Figure 42 for criterion 1 – *"Minimise unfavourable topographic conditions – slope of the terrain"* can be connected to the slope dataset. Then, these input areas, where the change happens, can be further investigated (for instance, the assignment of cost values). By performing their re-assignment one can further check if these areas remain sensitive.

In general, the identification of some degree of sensitivity is expected, especially when there is a high number of considered criteria (different criteria classes, criterion standardisation and weights assignments that are exposed to experts subjectivity). By a thorough investigation of the model for the Tlokweng Planning Area, the results of the sensitivity analysis are confirmed as being quite stable for the northern part of the study area (area marked with blue). This is where the northern road alignments are placed. Some sensitivity is apparent in the southern part of the study area through which the southern road alignments passes. These areas are mostly grouped on high terrain and could be further researched in more detail (area marked with red).

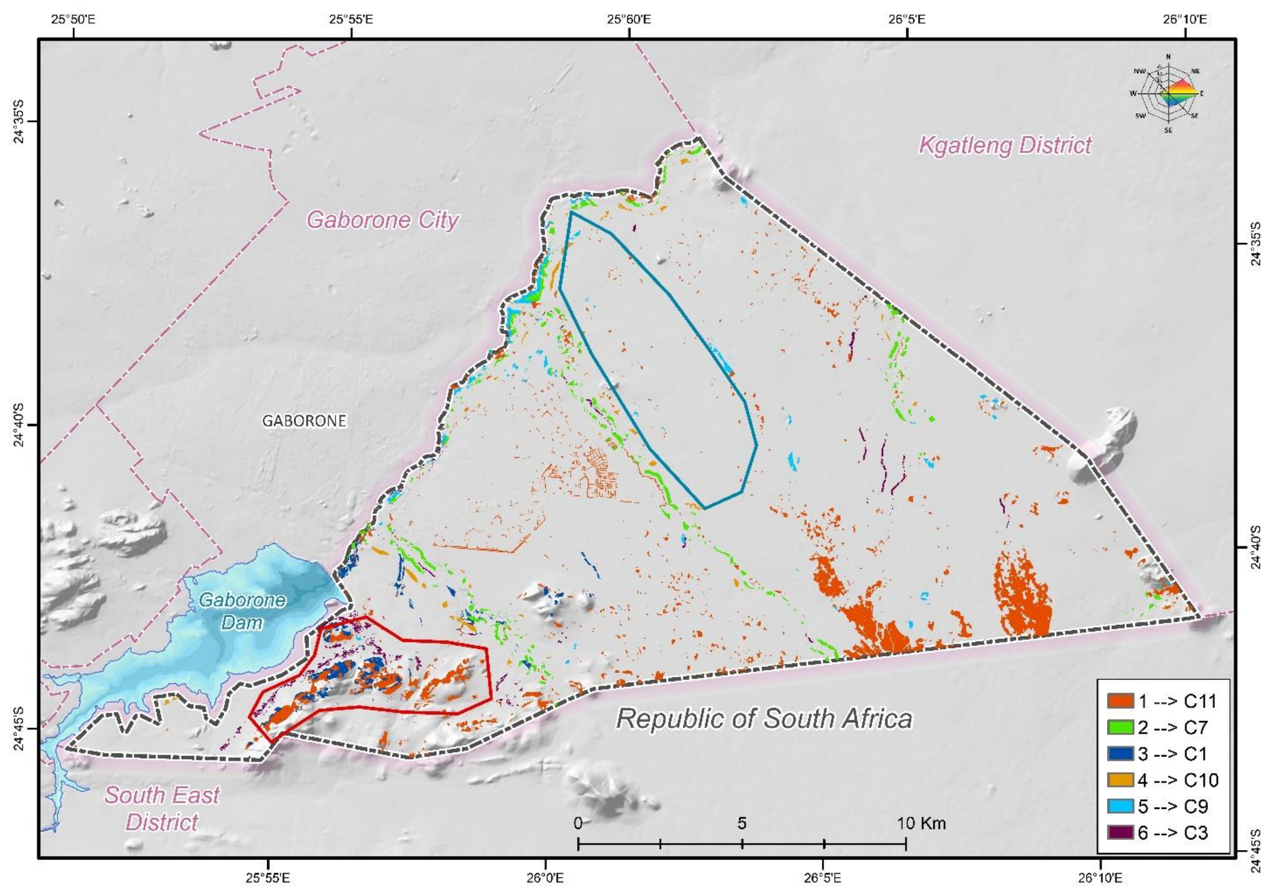

Figure 43. Defined sensitive areas within the Tlokweng Planning Study Area

Table 42. Ranking of criteria found to be senstive

#	Criteria	Ranking
11	Prioritise arable, grazing, forest and built-up land (Land Use / Land Cover)	**1**
7	Maximise distance to natural protected areas	**2**
1	Minimise unfavourable topographic conditions – slope of the terrain	**3**
10	Maximise distance to ground waters	**4**
9	Maximise distance to surface waters – dams and ponds	**5**
3	Minimise a number of by-pass crossings with rivers with high-order drainage	**6**

7 Conclusion

This thesis aimed at defining the MCE approach as an integrated part of an Environmental Impact Assessment (EIA), which will enable the optimal by-pass alignments running through the Tlokweng Planning area in Botswana to be found. This research is of high importance due to the fact that the Tlokweng area will undergo rapid development in the near future.

In order to achieve the aim, the following test questions have been outlined together with the main findings of this analysis:

1. *Which by-pass alignments are preferable in respect to economic, environmental and social factors?*

The application of MCE and GIS in solving different types of problem is well known. It has been gradually developed since the 1990s. In this thesis, the MCE approach is used to define the optimal by-pass alignments in respect to economic, environmental and social factors. Broadly speaking, economy, environment and society represent the main aspects of an Environmental Impact Assessment – EIA. EIA has been used in many countries and it is an integral part of large-scale projects with the main purpose of determining the economic, environmental and social impacts of such projects. This way, these impacts are defined before a final decision is made and, at the same time, is a major help in defining the final decision output.

13 criteria were defined and grouped into 3 themes: *economy, environment* and *society*. By applying the MCE approach within the GIS environment, criteria can be combined to give the solution – a by-pass alignment – in respect to the most-preferable theme. 3 by-pass alignments are produced depending on the preference. If more preference is given to the economic theme, then the model will produce a by-pass alignment which places more preference on the criteria belonging to it. Preference is determined through assigning different weights to themes. Weight assignments were defined using the Analytical Hierarchy Process (AHP).

In addition to the 3 mentioned by-pass alignments, the developed model also produces a 4th alternative named *"equal"* as it gives all themes the same preference when producing a by-pass alignment.

This way, by-pass alignments are successfully produced for both, the northern and southern parts of the Tlokweng Planning area.

2. *How do the results of the proposed multi-criteria evaluation (MCE) approach for a specific area of Tlokweng compare to the proposed by-pass alignment presented in the Tlokweng Development Plan 2025?*

According to the *"Revision of the Tlokweng Development Plan (2001-2025)"*, two by-pass alignments (northern and southern) are proposed (see Figure 1). As mentioned above, the model developed in this thesis gives 4 by-pass alignments, depending on the given preference to each of 3 themes – economy, environment and society. Therefore, 5 by-pass alignments are considered.

In order to rank alignments and make a reasonable comparison, an independent matrix with following 8 elements was considered:

1. *Number of agro land plots crossed*
2. *Number of objects demolished*
3. *Number of crossings with primary, secondary and tertiary roads*
4. *Number of crossings with rivers with 5^{th}, 6^{th}, 7^{th} and 8^{th} stream order*
5. *Earth works cut and fill (m3)*
6. *Total amount of asphalt and rocks used to build a by-pass (m3)*
7. *Length of tunnel (metres)*
8. *Length of bridge (metres)*

To perform ranking of by-pass alignments, the DEFINITE software package was used. According to the results obtained through MCE-GIS methodology, a by-pass alignment produced by giving the most preference to ***social theme*** is ranked best. This route is followed by equal, economic and environmental routes.

What differentiates social from other alignments is mostly the contribution of element C1 – the crossed number of agro lands plots. Through the Analytical Hierarchy Process (AHP) the most weight is assigned to this element because the Tlokweng community considers it of great importance to protect this type of land. On the other hand, within the social theme agro land, as one land-use type, receives the highest costs, thus making it the best compared to others.

On the other hand, the planned alignment does not use the MCE-GIS approach; public involvement is highly dominant in the adopted approach.

3. *Which criteria are most sensitive to weight changes by conducting one-at-a-time sensitivity analysis?*

One-At-a-Time (OAT) sensitivity analysis was performed to obtain more insights and a better understanding of the developed model. In this analysis the main purpose was to investigate the robustness of the entire model when each criterion weight is changed in the range -20% to +20%. To find the criteria that affect the model's robustness, it was necessary to apply a statistical test for zero proportion as the total number of changed cells within a raster dataset (cell size 5 x 5 metres) is substantially less than the total number of cells within a study area (over 11 million). Statistical tests show that 6 criteria were identified as sensitive. The most sensitive is criterion 11 – "*Prioritise arable, grazing, forest and built-up land (Land Use / Land Cover)*". Among criteria that show sensitivity, the least sensitive is 3 – "*Minimise a number of by-pass crossings with rivers with high-order drainage*".

Sensitivity can be spatially presented by locating the areas where the cell changes happen within the studied space. Once recognised, these areas could be further linked to the original dataset (model inputs) they belong to. The focus should then be the areas (spatial data) of the original dataset to increase the robustness of the model. This could be done perhaps by conducting further research. One of the aspects that can be researched in more detail is cost value assignments to those areas where the cell changes occur.

8 Recommendations

The following recommendations could be considered:

1. *Including expert teams when defining the criteria, criteria standardisation and criteria weights*
2. *Conducting global sensitivity analysis approach*
3. *Using algorithm with larger connectivity pattern for deriving the least-cost path*
4. *Extending the study area by including the part belonging to Gaborone*
5. *Developing an additional module that performs MCE and is more user-friendly*

8.1 Including expert teams when defining the criteria, criteria standardisation and criteria weights

The criteria used in this thesis were based on a literature review, availability of spatial data and the official government document for road design in Botswana.

Many stakeholders are included in the Environmental Impact Assessment (EIA). Opinions between stakeholders differ and it is also important to define the criteria from their perspective. This means that some criteria defined in this thesis could be changed – either excluded or new ones added. For example, economic themes are mainly considered from the perspective of construction costs that in most cases belong to road authority costs. Besides this cost type one can define others such as community costs, which would include travel time costs, accident costs, etc… Every new road infrastructure generates traffic and affects travel patterns. Thus, one can think that the costs and benefits posed to the community could also be included in these analyses.

Further, criterion standardisation is completed on a scale from 1 to 5. These values are seen as costs where the highest preference is given to 1 as the least cost, and least preference to 5 as the highest. Standardisation was based on expert opinion which is highly subjective. Thus, it is recommended to include an expert team during this process.

Similarly to criterion standardisation, defining criterion weight within each theme and weight among the themes was based on expert opinion. Therefore, an expert team could also be included when defining criterion weights.

8.2 Conducting global sensitivity analysis approach

In respect to sensitivity analysis, several aspects are worth pointing out.

Firstly, in this thesis One-At-a-Time (OAT) sensitivity analysis was used to check how the changing of criterion weights affects the model output. In OAT sensitivity analysis one variable is changed at a time while others remain unchanged. The main disadvantage is that it cannot capture nonlinearities and correlations among input variables (European Commission, 2015; Saltelli et al., 2004). Some correlation (interactions) could exist among the criteria. Thus, when one changes a criterion weight, the effect is not just due to the weight change of that criteria itself, but also to changes to other correlated criteria. Therefore, a *"global"* approach to sensitivity analysis could be more appropriate, which would use a combination of simultaneous variable changes to learn more about robustness of the results.

Yet another aspect is that OAT sensitivity analysis is performed on all criteria within each theme. Besides combining criteria within each theme, the results – the proposed by-pass alignments produced by GIS – are greatly dependent on the weights assigned to each theme. Changing these assigned weights has was taken into consideration when conducting the sensitivity analysis. Therefore, it would be beneficial to include this as well and see how it affects the results. One can expect that changing the theme weights will affect more results than only changing each criterion weight within each theme.

Sensitivity analysis is conducted based on criterion weight changing. This is only one aspect prone to subjectivity within the entire MCE. Thus, it could be reasonable to include other parts also exposed to subjectivity in MCE. For example, one can perform sensitivity analysis in respect to criteria standardisation.

All the above-mentioned facts regarding sensitivity analysis means that this analysis needs to be carefully designed. Moreover, many aspects of the model are in relation to each other which increases the complexity and affects the results in different ways. For example, the results are affected by the first layer of the model including different criteria within each theme and the second layer that deals with a combination of different themes.

8.3 Using algorithm with larger connectivity pattern for deriving the least-cost path

The algorithm used to produce by-pass road alignments is based on node-link cell representation and a 3 x 3 neighbour (see Figure 6). This means that the movement of the path is influenced by 2 limitations: the movement to one of the eight neighbouring cells and the direction (eight principle directions used in a back-link raster). As a result, the by-pass road alignment (least-cost path) could follow a zigzag pattern. To avoid this different algorithms can be used that propose movement greater than one cell (Goncalves, 2010). Antikainen, (2013) proposed another approach in which larger connectivity patterns to neighbouring cells are used, for example 5 x 5, 7 x 7 and 9 x 9.

8.4 Extending the study area by including the part belonging to Gaborone

The study area in this thesis is Tlokweng. The two points, located on the border with Gaborone, are determined according to the Tlokweng Development Plan. From these points by-pass alignments should further continue towards Gaborone and be connected to the A1 motorway with the connections outside the Gaborone city perimeter on the southeast and northwest. Thus, it would be reasonable to extend the study area to include the part belonging to Gaborone and consider the results in respect to this. The main prerequisite for performing more extended analysis is to have spatial data for this part available as well.

8.5 Developing an additional module that performs MCE and is more user-friendly

The ModelBuilder tool within the ArcGIS environment was used in this thesis to find a solution for the base case scenario. The advantage is that one can very quickly test different scenarios. For example, one can use different criterion standardisation values, different criteria weights and different weights among the themes. This approach is also flexible in that the points, between which the by-pass alignment should be produced, could also be updated and by running the ModelBuilder again a new set of solutions will be obtained. However, to update criteria weights, for example, one has to calculate them outside of ArcGIS and then insert them into the model. This means that the stakeholders included in the Environmental Impact Assessment (EIA) process and those interested in the results will require knowledge of GIS systems to test different scenarios and produce results.

Depending on the level of integration of MCE techniques within GIS, 3 strategies (couplings) have been recognised so far: *full, tight and loose* coupling. A *full* coupling means there exists a single software package able to perform a set of different MCE techniques, and is provided by the vendor. A *tight* coupling means there exists a common user interface and data management, which is achieved through package customisation. Finally, the third strategy – *loose* coupling – means there exists data exchange between packages, MCE and GIS. Here the file exchange mechanism is used. MCE techniques are included in a separate piece of software. A user runs every step of MCE in sequence to obtain results. These results can be further sent to the GIS package to be displayed and visualised (Nyerges & Jankowski, 2010; Greene, 2011). According to this categorisation, from the aspect of integration, the way MCE is handled within this thesis can be classified under *loose coupling strategy*. To make it easier from an analysis point of view, it would be beneficial to develop modules able to handle different types of approaches used in MCE (tight coupling strategy). This way the new criteria could also be included and tested easily.

From a user's point of view, it would also be useful to consider developing online maps, where it would be possible to perform the entire MCE and see the results. GIS systems have recently undergone rapid development and such tools are available. Utilisation of these approaches is especially useful during meetings as results are quickly available to attendees. This way communication becomes clearer and avoids possible misunderstandings that would otherwise often occur.

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10 Appendix I – Results from ModelBuilder

Step 1 – Pre-processing data (see Figure 25)

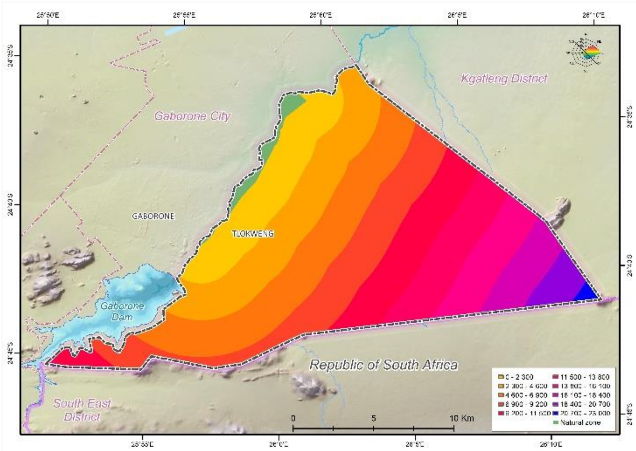


Figure 44. Euclidian distance for natural protected areas

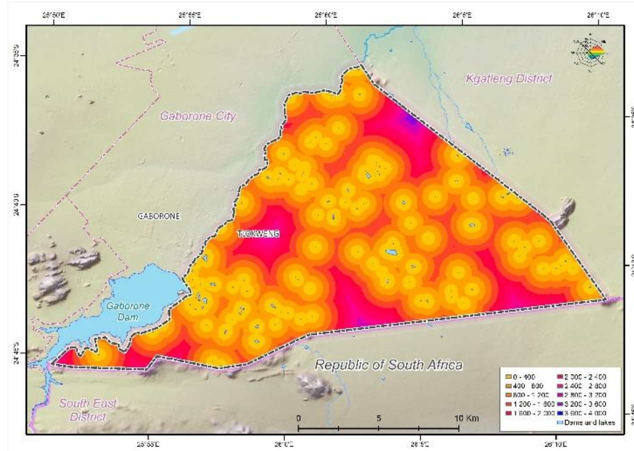


Figure 45. Euclidian distance for surface waters – dams and lakes

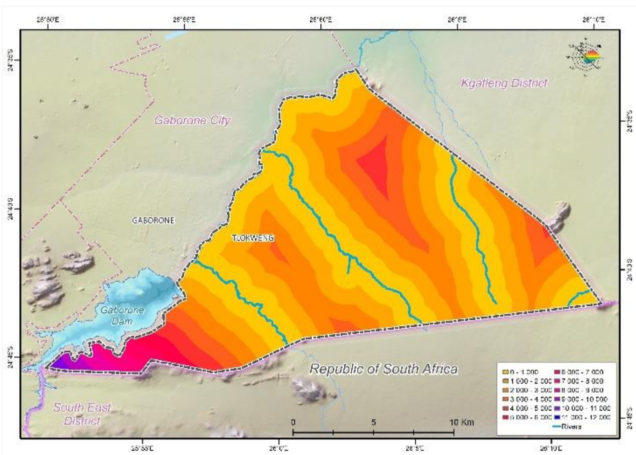


Figure 46. Euclidian distance for the main river system

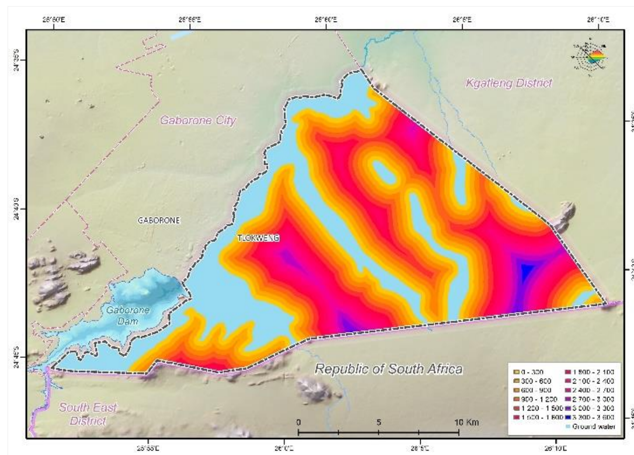


Figure 47. Euclidian distance for the ground water system

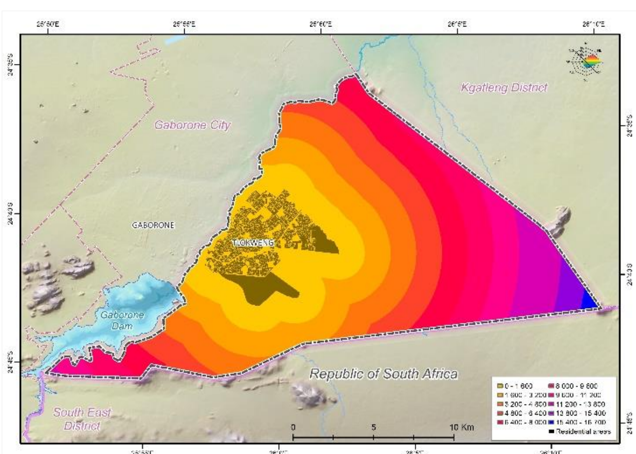


Figure 48. Euclidian distance for residential areas

Step 3 – Criteria standardisation (see Figure 25)

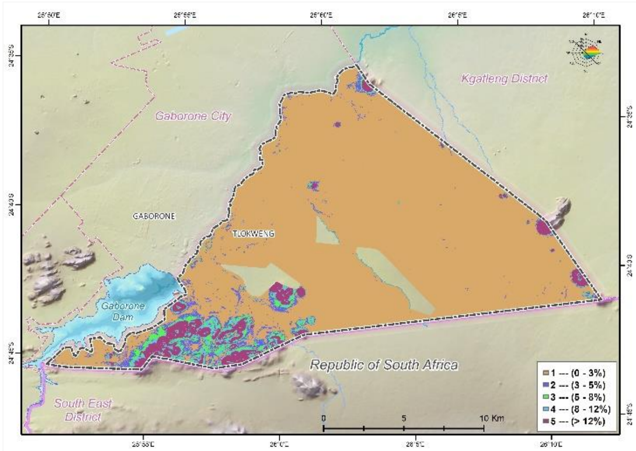


Figure 49. Reclassified slope (%) within the Tlokweng study area

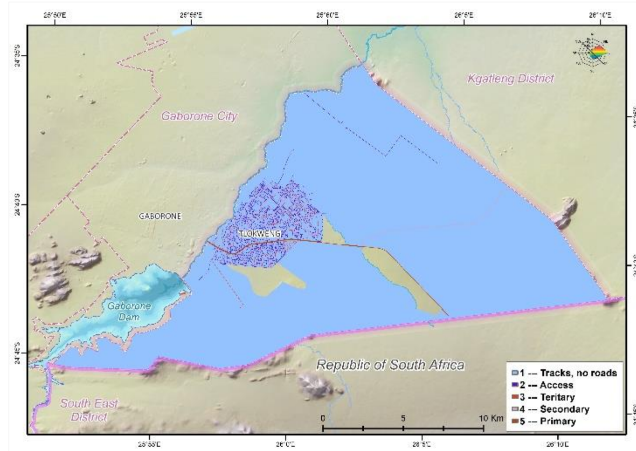


Figure 50. Reclassified road classes within the Tlokweng study area

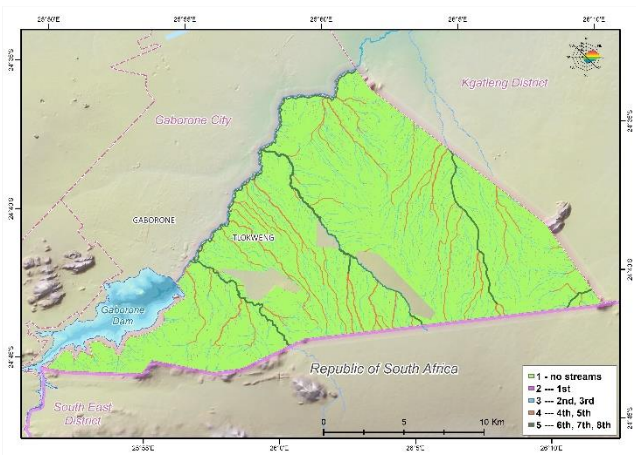


Figure 51. Reclassified stream classes within the Tlokweng study area

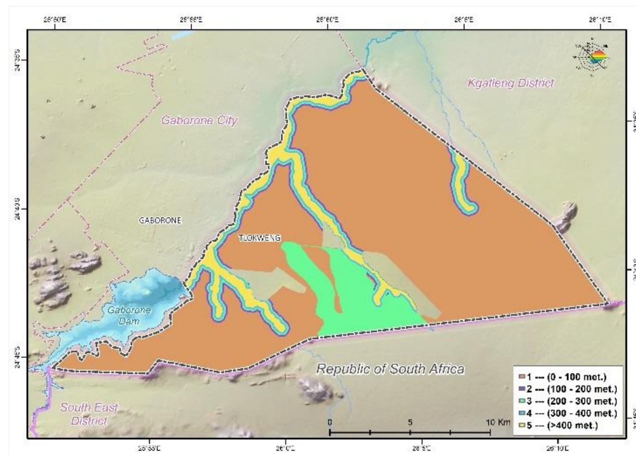


Figure 52. Reclassified flooding areas within the Tlokweng study area

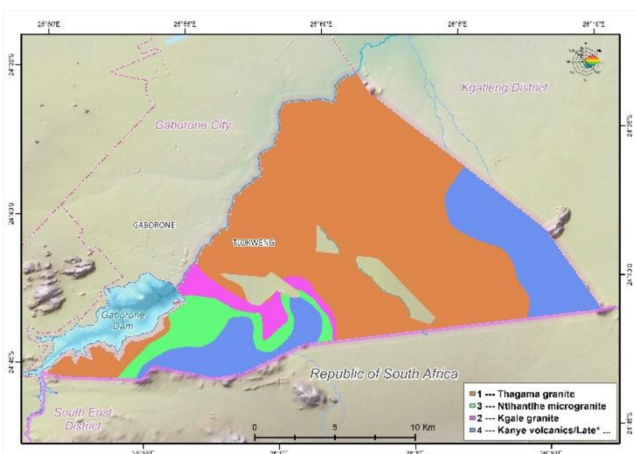


Figure 53. Reclassified geology type within the Tlokweng study area

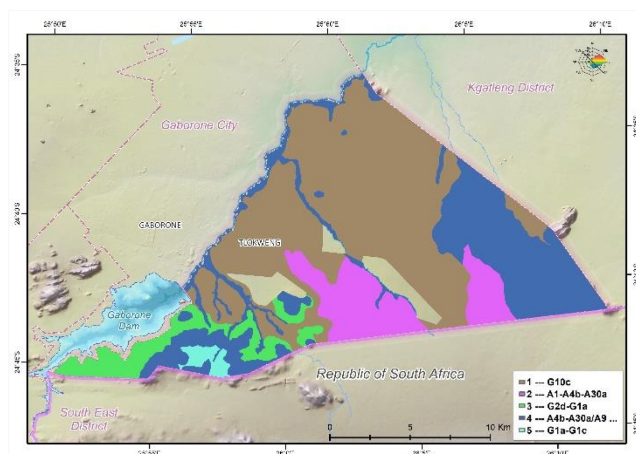


Figure 54. Reclassified soil type within the Tlokweng study area

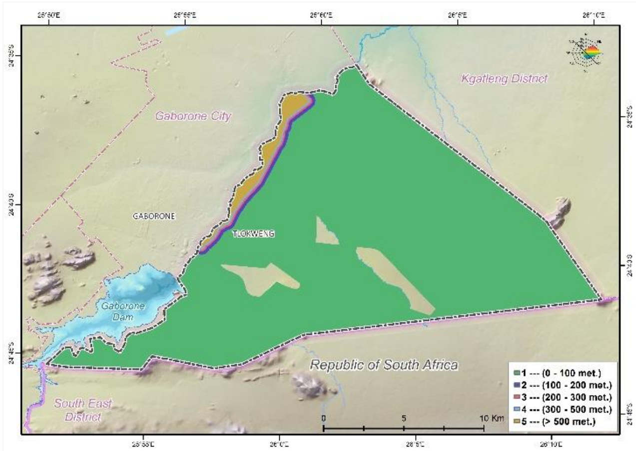


Figure 55. Reclassified distance from natural protected areas within the Tlokweng study area

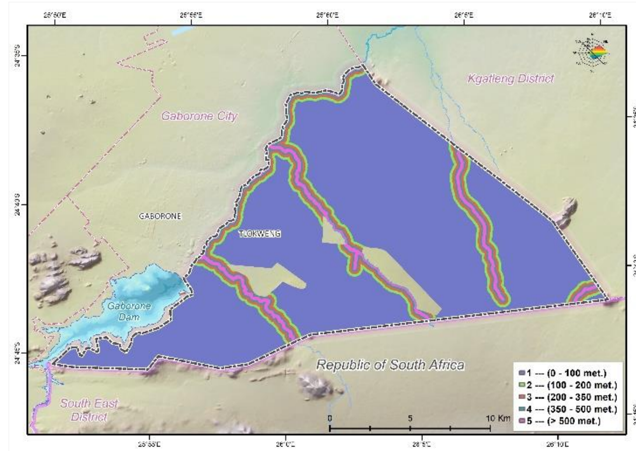


Figure 56. Reclassified distance from major rivers stream within the Tlokweng study area

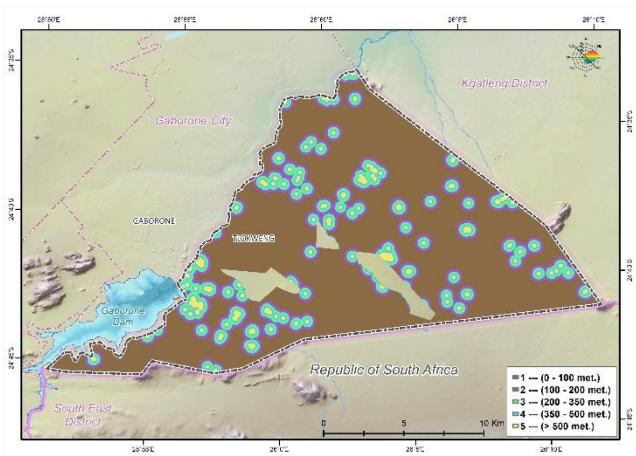


Figure 57. Reclassified distance from surface waters – dams and ponds within the Tlokweng study area

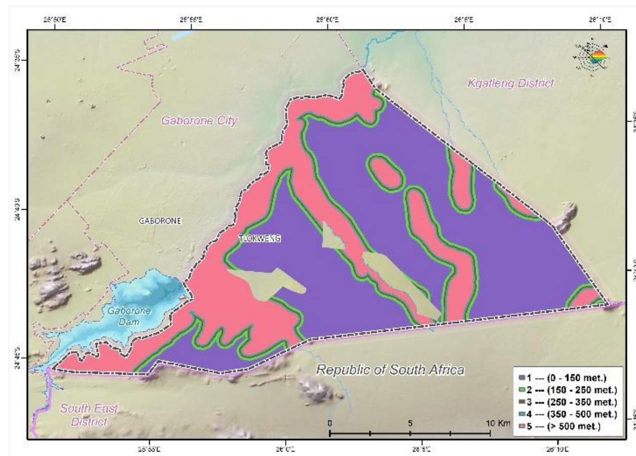


Figure 58. Reclassified distance from ground waters within the Tlokweng study area

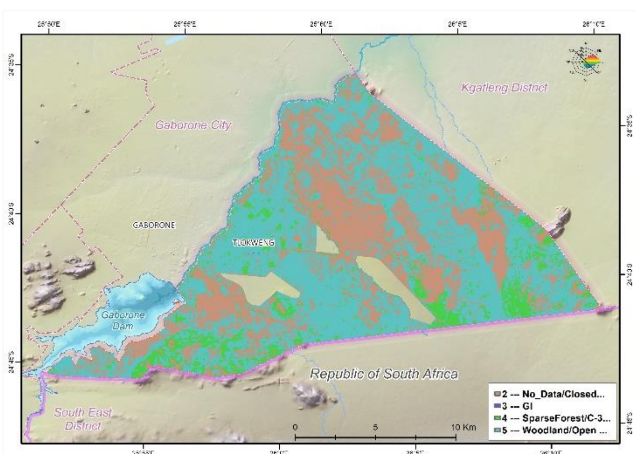


Figure 59. Reclassified land use / land cover within the Tlokweng study area

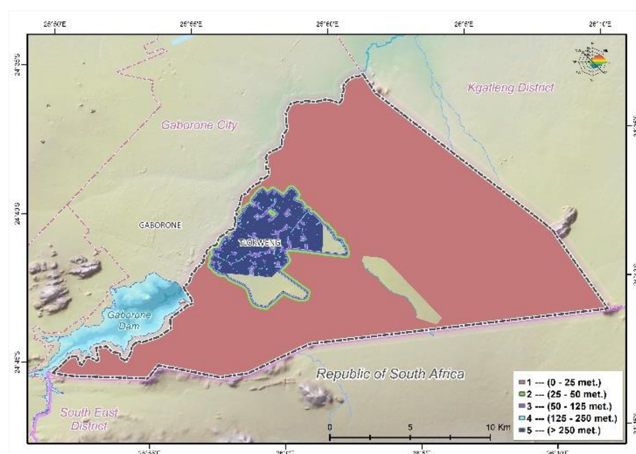


Figure 60. Reclassified distance from residential areas within the Tlokweng study area (noise pollution)

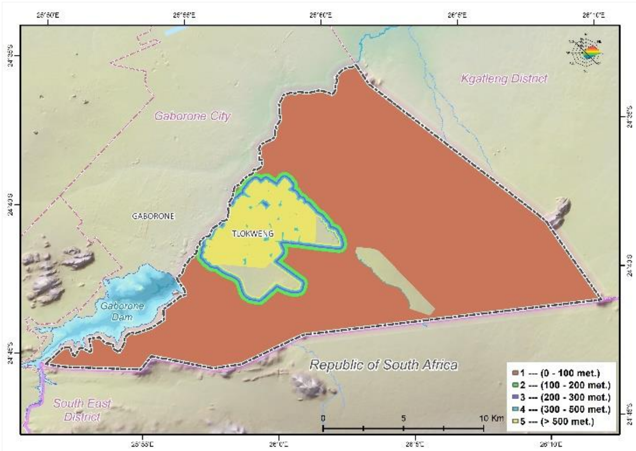


Figure 61. Reclassified distance from residential areas within the Tlokweng study area (air pollution)

Step 4 – Combining criteria within each theme (see Figure 25)

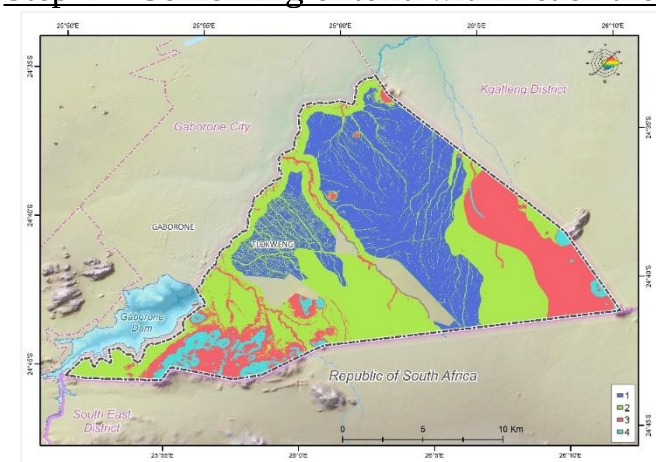


Figure 62. Costs of combined criteria within economic theme

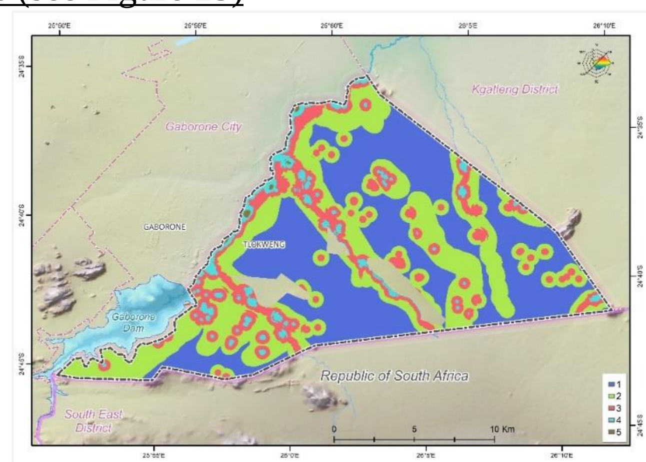


Figure 63. Costs of combined criteria within the environmental theme

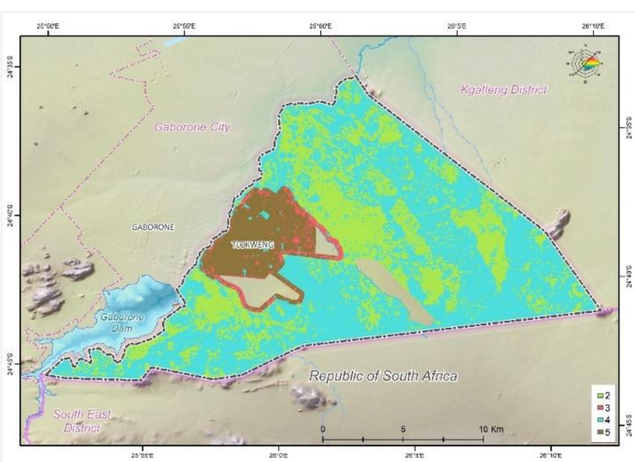


Figure 64. Costs of combined criteria within the social theme

Step 7 – The least accumulative cost distance for northern by-pass alignment (see Figure 25)

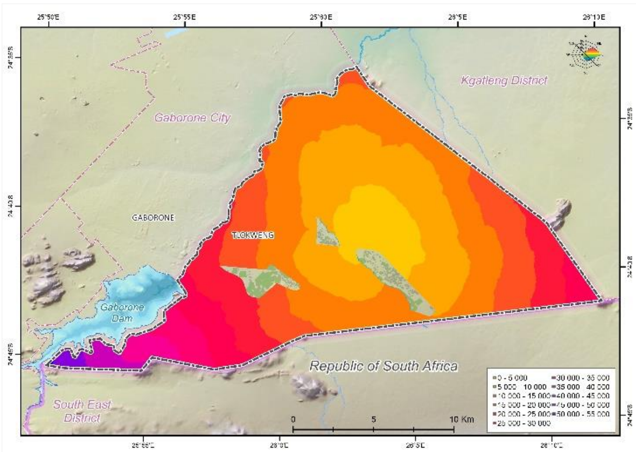


Figure 65. Cost distance for economic theme

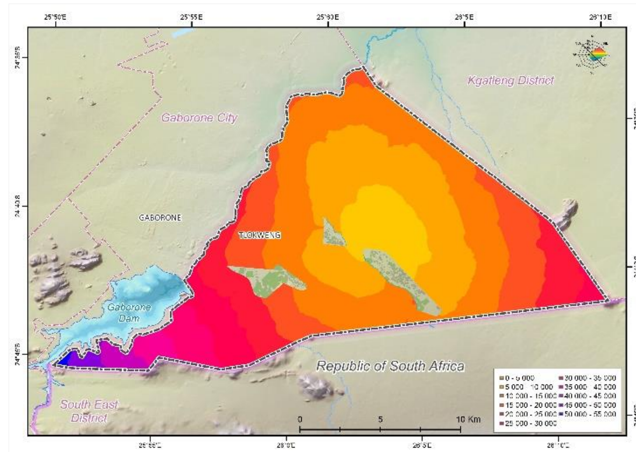


Figure 66. Cost distance for environmental theme

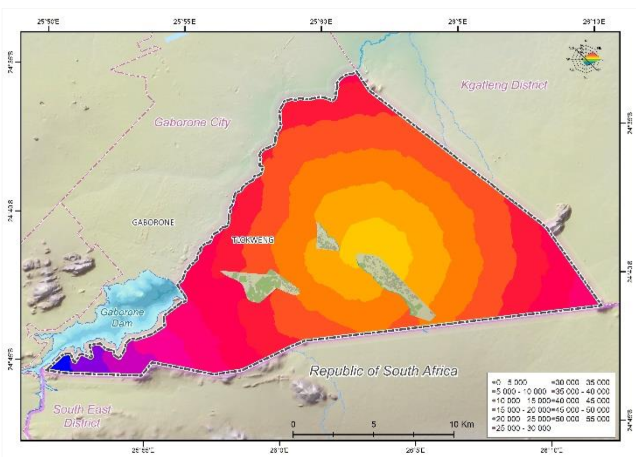


Figure 67. Cost distance for social theme

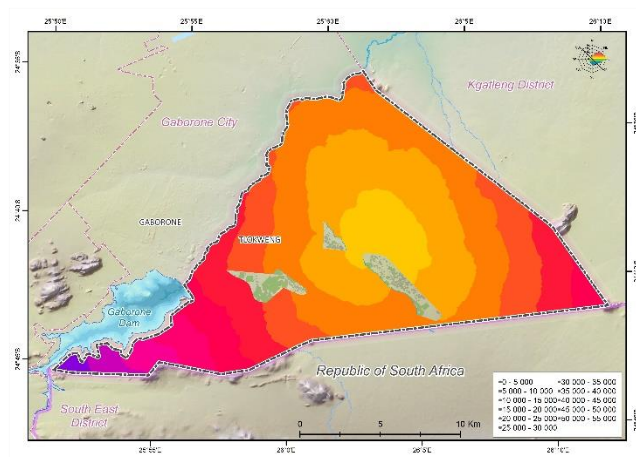


Figure 68. Cost distance for equal theme

Step 7 – The least accumulative cost distance for southern by-pass alignment (see Figure 25)

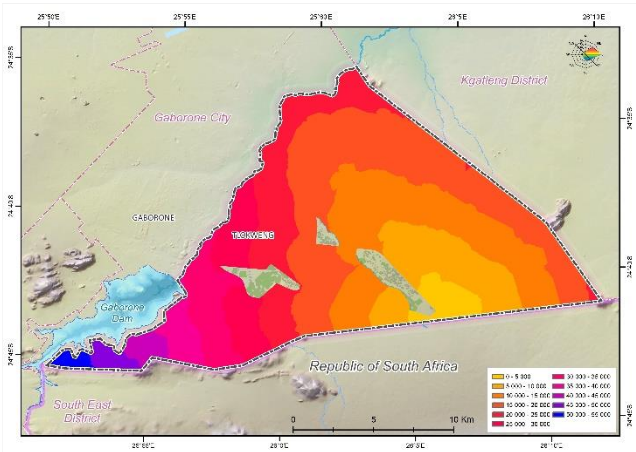


Figure 69. Cost distance for economic theme

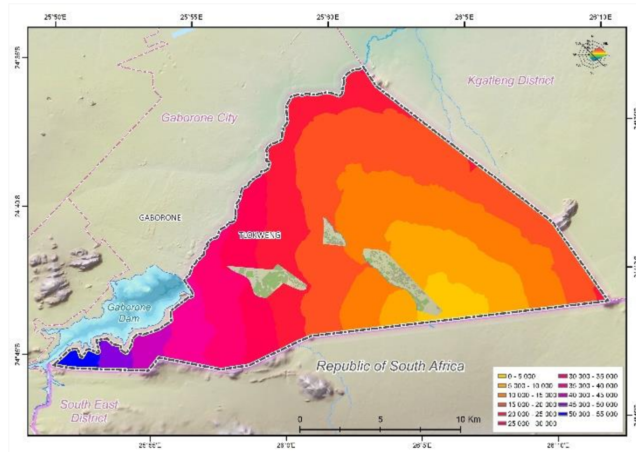


Figure 70. Cost distance for environmental theme

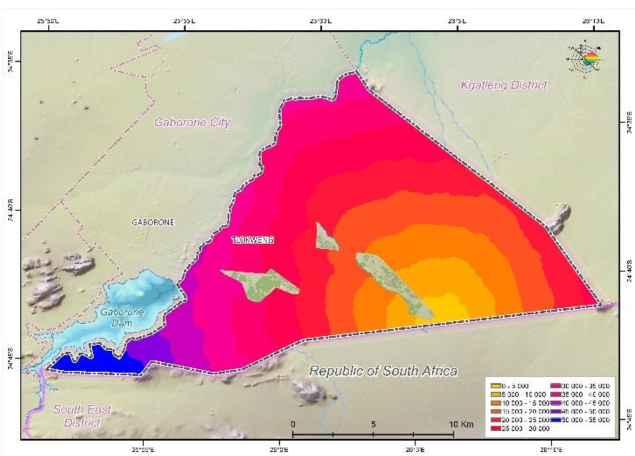


Figure 71. Cost distance for social theme

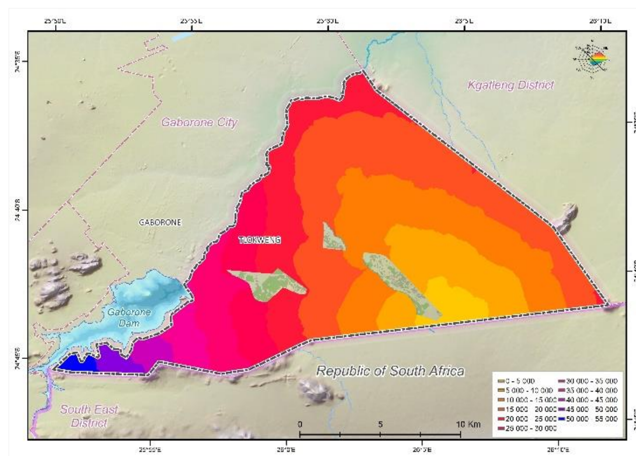
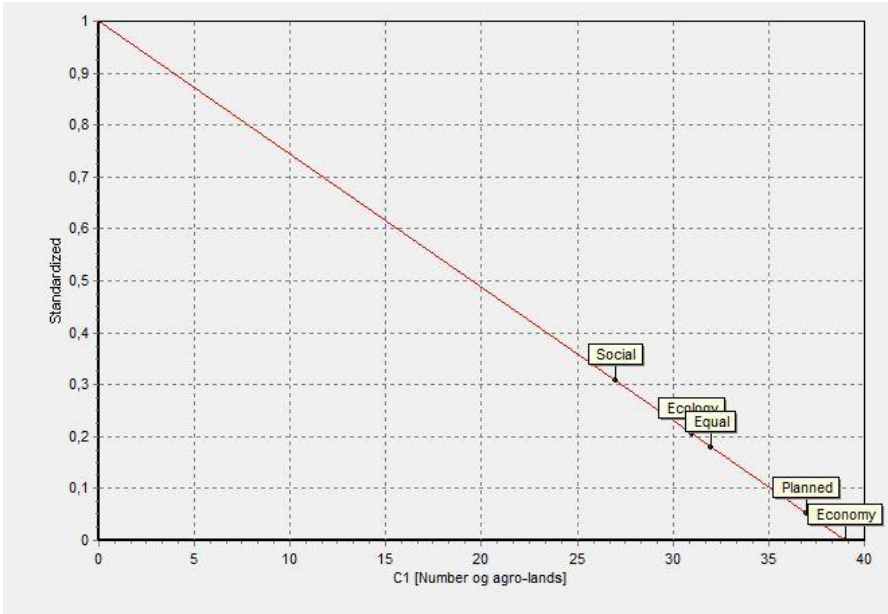


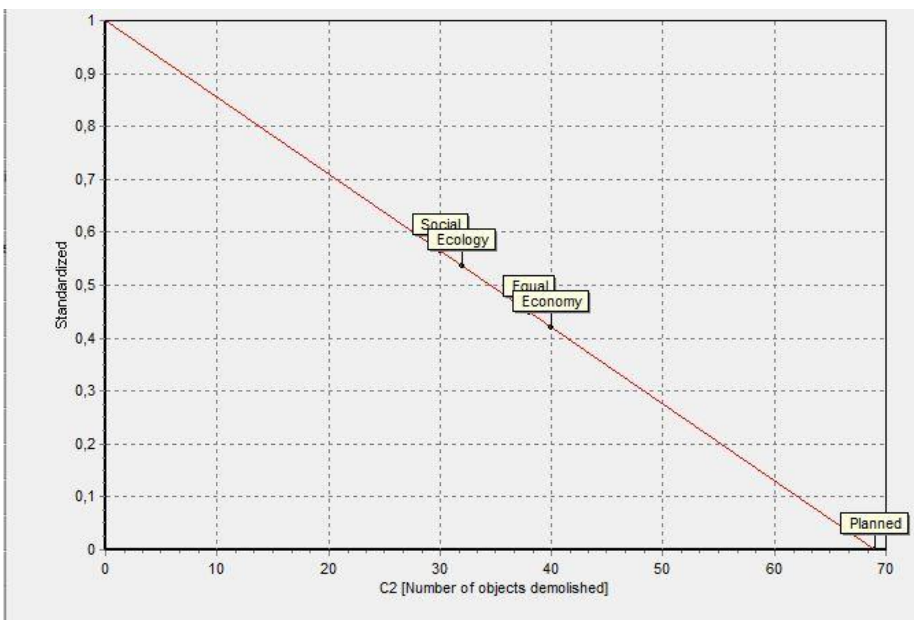
Figure 72. Cost distance for equal theme

11 Appendix II – Standardisation of elements of the independent matrix within the DEFINITE software package



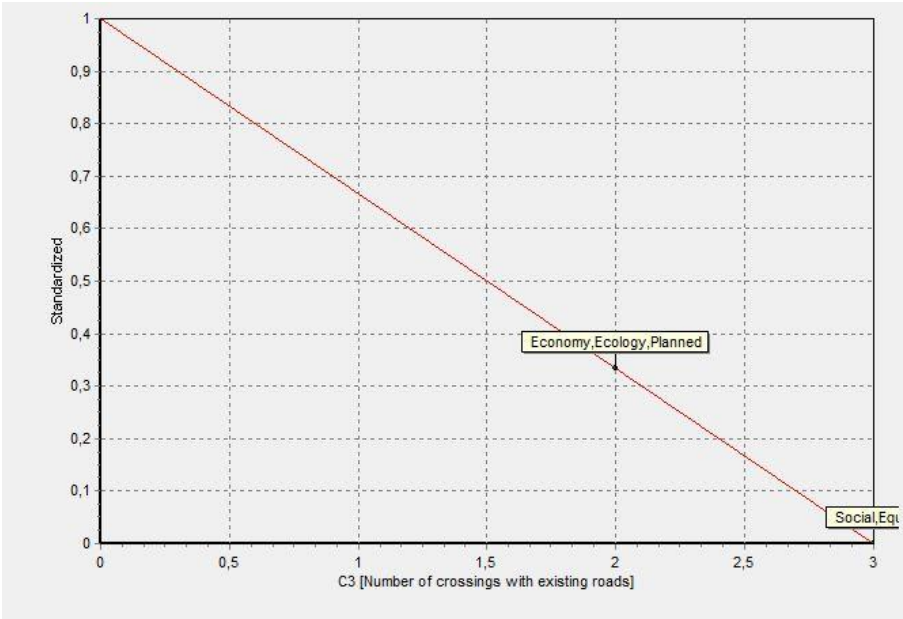
	C/B	Unit	Economy	Ecology	Social	Equal	Planned
C1	⊖	Number og agro-lands	39	31	27	32	37
			0,00	0,21	0,31	0,18	0,05

Figure 73. Standardisation of element C1 – Number of agro plots crossed



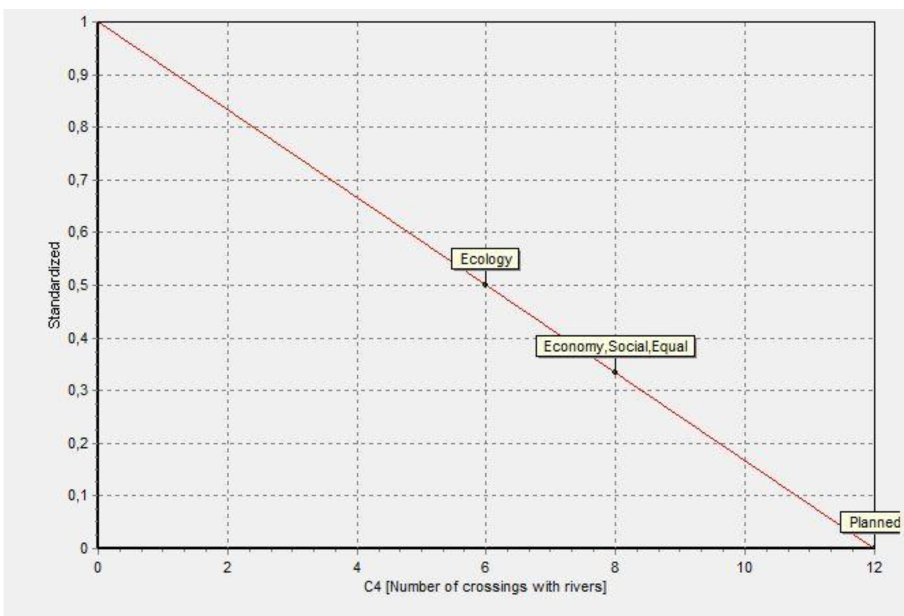
	C/B	Unit	Economy	Ecology	Social	Equal	Planned
C2	⊖	Number of objects demolished	40	32	30	38	69
			0,42	0,54	0,57	0,45	0,00

Figure 74. Standardisation of element C2 – Number of objects demolished



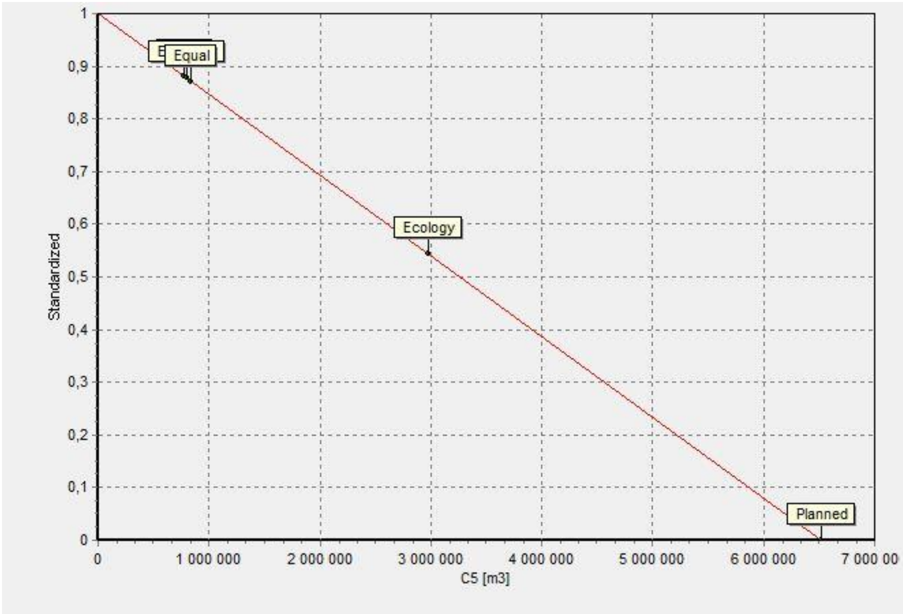
	C/B	Unit	Economy	Ecology	Social	Equal	Planned
C3		Number of crossings with existing roads	2	2	3	3	2
			0,33	0,33	0,00	0,00	0,33

Figure 75. Standardisation of element C3 – Number of crossings with primary, secondary and tertiary roads



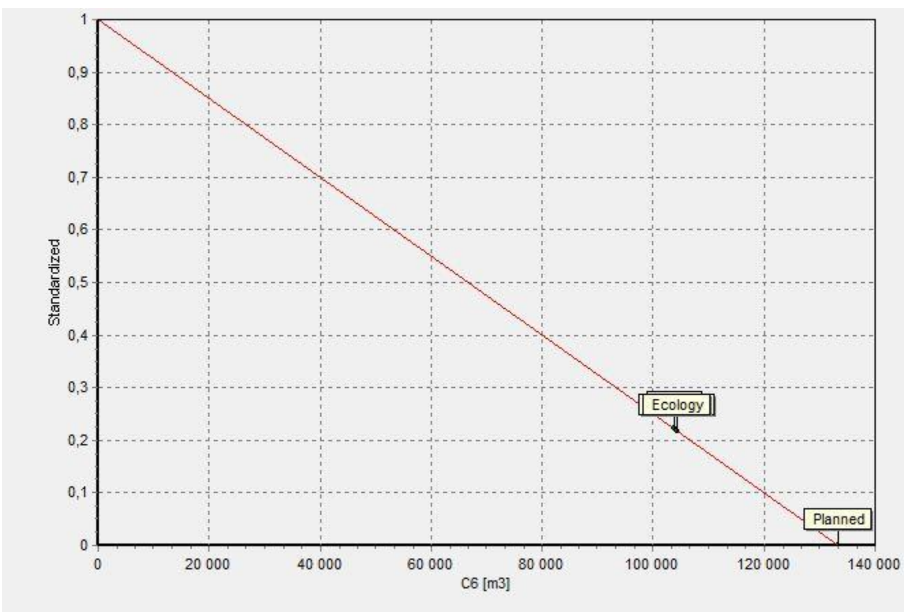
	C/B	Unit	Economy	Ecology	Social	Equal	Planned
C4		Number of crossings with rivers	8	6	8	8	12
			0,33	0,50	0,33	0,33	0,00

Figure 76. Standardisation of element C4 – Number of crossings with rivers (5th, 6th, 7th and 8th stream order)



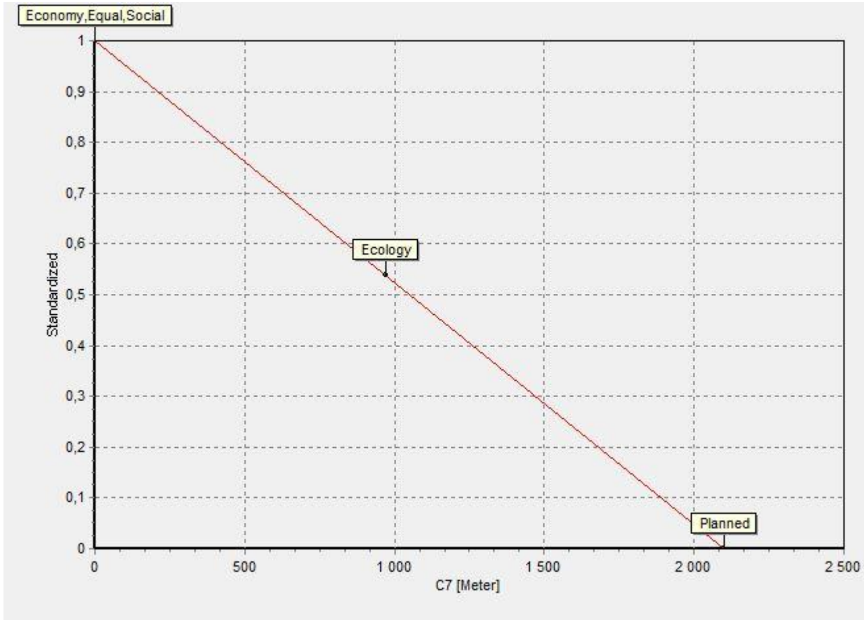
	C/B	Unit	Economy	Ecology	Social	Equal	Planned
C5	●	m3	794870	2980199	780636	842197	6522557
			0,88	0,54	0,88	0,87	0,00

Figure 77. Standardisation of element C5 – Earth works cut and fill (m3)



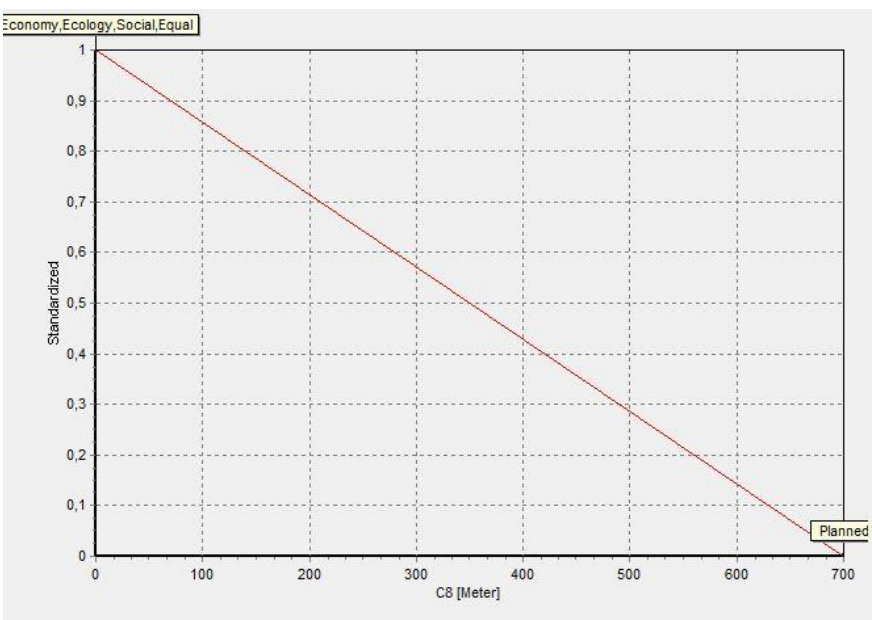
	C/B	Unit	Economy	Ecology	Social	Equal	Planned
C6	●	m3	104269	104272	103824	104238	133446
			0,22	0,22	0,22	0,22	0,00

Figure 78. Standardisation of element C6 – Total amount of asphalt and rocks (m3)



	C/B	Unit	Economy	Ecology	Social	Equal	Planned
C7		Meter	0	970	0	0	2100
			1,00	0,54	1,00	1,00	0,00

Figure 79. Standardisation of element C7 – Length of tunnel (metres)



	C/B	Unit	Economy	Ecology	Social	Equal	Planned
C8		Meter	0	0	0	0	700
			1,00	1,00	1,00	1,00	0,00

Figure 80. Standardisation of element C8 – Length of bridge (metres)

12 Appendix III – Sensitivity analysis

Table 43. Summary table showing changes in cell cost values when the weight of criterion C1 – "Minimise unfavourable topographic conditions – slope of the terrain" is changed

%	Criterion weight values						Total number of cells in every cost class					Percentage change (%)				
PC	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
-20	0.2320	0.1082	0.1731	0.0757	0.2272	0.1839	774151	6081596	4292227	195451	0	0	-1	4	-31	0
-19	0.2349	0.1078	0.1724	0.0754	0.2263	0.1832	774151	6081584	4292138	195552	0	0	-1	4	-31	0
-18	0.2378	0.1074	0.1718	0.0751	0.2254	0.1825	774151	6089519	4284172	195583	0	0	-1	3	-31	0
-17	0.2407	0.1069	0.1711	0.0749	0.2246	0.1818	774151	6089519	4284301	195454	0	0	-1	3	-31	0
-16	0.2436	0.1065	0.1705	0.0746	0.2237	0.1811	774151	6089519	4284301	195454	0	0	-1	3	-31	0
-15	0.2465	0.1061	0.1698	0.0743	0.2229	0.1804	774151	6089845	4283947	195482	0	0	-1	3	-31	0
-14	0.2494	0.1057	0.1691	0.0740	0.2220	0.1797	774151	6088364	4276034	204876	0	0	-1	3	-28	0
-13	0.2523	0.1053	0.1685	0.0737	0.2212	0.1790	774151	6088115	4276283	204876	0	0	-1	3	-28	0
-12	0.2552	0.1049	0.1678	0.0734	0.2203	0.1783	774151	6119165	4246306	203803	0	0	0	2	-29	0
-11	0.2581	0.1045	0.1672	0.0731	0.2194	0.1776	774151	6119165	4246306	203803	0	0	0	2	-29	0
-10	0.2610	0.1041	0.1665	0.0729	0.2186	0.1769	774151	6131342	4234129	203803	0	0	0	2	-29	0
-9	0.2639	0.1037	0.1659	0.0726	0.2177	0.1762	774151	6131342	4234129	203803	0	0	0	2	-29	0
-8	0.2668	0.1033	0.1652	0.0723	0.2169	0.1756	774151	6131342	4234129	203803	0	0	0	2	-29	0
-7	0.2697	0.1029	0.1646	0.0720	0.2160	0.1749	774151	6137837	4146111	285326	0	0	0	0	0	0
-6	0.2726	0.1025	0.1639	0.0717	0.2151	0.1742	774151	6137837	4146111	285326	0	0	0	0	0	0
-5	0.2755	0.1020	0.1633	0.0714	0.2143	0.1735	774151	6137830	4146118	285326	0	0	0	0	0	0
-4	0.2784	0.1016	0.1626	0.0711	0.2134	0.1728	774151	6138073	4145978	285223	0	0	0	0	0	0
-3	0.2813	0.1012	0.1620	0.0709	0.2126	0.1721	774151	6138061	4145990	285223	0	0	0	0	0	0
-2	0.2842	0.1008	0.1613	0.0706	0.2117	0.1714	774151	6139932	4144107	285235	0	0	0	0	0	0
-1	0.2871	0.1004	0.1607	0.0703	0.2109	0.1707	774151	6139858	4144178	285238	0	0	0	0	0	0
0	**0.2900**	**0.1000**	**0.1600**	**0.0700**	**0.2100**	**0.1700**	**774151**	**6139865**	**4144171**	**285238**	**0**	**-**	**-**	**-**	**-**	**-**
1	0.2929	0.0996	0.1593	0.0697	0.2091	0.1693	774151	6139668	4144308	285298	0	0	0	0	0	0
2	0.2958	0.0992	0.1587	0.0694	0.2083	0.1686	774151	6139668	4144308	285298	0	0	0	0	0	0
3	0.2987	0.0988	0.1580	0.0691	0.2074	0.1679	774151	6140322	4143772	285180	0	0	0	0	0	0
4	0.3016	0.0984	0.1574	0.0689	0.2066	0.1672	774151	6140322	4147688	281264	0	0	0	0	-1	0
5	0.3045	0.0980	0.1567	0.0686	0.2057	0.1665	774151	6135520	4135485	298269	0	0	0	0	5	0
6	0.3074	0.0975	0.1561	0.0683	0.2049	0.1658	774151	6135520	4135485	298269	0	0	0	0	5	0
7	0.3103	0.0971	0.1554	0.0680	0.2040	0.1651	774151	6135520	4135485	298269	0	0	0	0	5	0
8	0.3132	0.0967	0.1548	0.0677	0.2031	0.1644	774151	6135505	4135821	297948	0	0	0	0	4	0
9	0.3161	0.0963	0.1541	0.0674	0.2023	0.1638	774151	6135505	4135821	297948	0	0	0	0	4	0
10	0.3190	0.0959	0.1535	0.0671	0.2014	0.1631	774151	6139607	4131515	298152	0	0	0	0	5	0
11	0.3219	0.0955	0.1528	0.0669	0.2006	0.1624	774151	6139607	4131515	298152	0	0	0	0	5	0
12	0.3248	0.0951	0.1522	0.0666	0.1997	0.1617	774151	6139548	4128174	301552	0	0	0	0	6	0
13	0.3277	0.0947	0.1515	0.0663	0.1988	0.1610	774151	6139548	4128174	301552	0	0	0	0	6	0
14	0.3306	0.0943	0.1509	0.0660	0.1980	0.1603	774151	6142685	4125246	301343	0	0	0	0	6	0
15	0.3335	0.0939	0.1502	0.0657	0.1971	0.1596	774151	6142343	4125587	301344	0	0	0	0	6	0
16	0.3364	0.0935	0.1495	0.0654	0.1963	0.1589	774151	6142343	4125587	301344	0	0	0	0	6	0
17	0.3393	0.0931	0.1489	0.0651	0.1954	0.1582	774151	6142261	4125114	301899	0	0	0	0	6	0
18	0.3422	0.0926	0.1482	0.0649	0.1946	0.1575	774151	6139600	4128467	301207	0	0	0	0	6	0
19	0.3451	0.0922	0.1476	0.0646	0.1937	0.1568	774151	6139600	4128467	301207	0	0	0	0	6	0
20	0,3480	0,0918	0,1469	0,0643	0,1928	0,1561	774151	6139593	4128474	301207	0	0	0	0	6	0

Table 44. Summary table showing changes in cell cost values when the weight of criterion C2 – "Minimise a number of by-pass crossings with roads with high priority" is changed

%	Criterion weight values						Total number of cells in every cost class					Percentage change (%)				
PC	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
-20	0.2964	0.0800	0.1636	0.0716	0.2147	0.1738	774151	6129369	4136242	303541	122	0	0	0	6	0
-19	0.2961	0.0810	0.1634	0.0715	0.2144	0.1736	774151	6129369	4136242	303541	122	0	0	0	6	0
-18	0.2958	0.0820	0.1632	0.0714	0.2142	0.1734	774151	6129369	4136242	303541	122	0	0	0	6	0
-17	0.2955	0.0830	0.1630	0.0713	0.2140	0.1732	774151	6129369	4136242	303541	122	0	0	0	6	0
-16	0.2952	0.0840	0.1628	0.0712	0.2137	0.1730	774151	6130342	4135737	303073	122	0	0	0	6	0
-15	0.2948	0.0850	0.1627	0.0712	0.2135	0.1728	774151	6130342	4135737	303073	122	0	0	0	6	0
-14	0.2945	0.0860	0.1625	0.0711	0.2133	0.1726	774151	6130342	4135737	303073	122	0	0	0	6	0
-13	0.2942	0.0870	0.1623	0.0710	0.2130	0.1725	774151	6130342	4135737	303073	122	0	0	0	6	0
-12	0.2939	0.0880	0.1621	0.0709	0.2128	0.1723	774151	6130342	4135743	303067	122	0	0	0	6	0
-11	0.2935	0.0890	0.1620	0.0709	0.2126	0.1721	774151	6130342	4135743	303067	122	0	0	0	6	0
-10	0.2932	0.0900	0.1618	0.0708	0.2123	0.1719	774151	6130327	4135719	303106	122	0	0	0	6	0
-9	0.2929	0.0910	0.1616	0.0707	0.2121	0.1717	774151	6130327	4135719	303106	122	0	0	0	6	0
-8	0.2926	0.0920	0.1614	0.0706	0.2119	0.1715	774151	6139688	4144347	285239	0	0	0	0	0	0
-7	0.2923	0.0930	0.1612	0.0705	0.2116	0.1713	774151	6139688	4144347	285239	0	0	0	0	0	0
-6	0.2919	0.0940	0.1611	0.0705	0.2114	0.1711	774151	6139688	4144347	285239	0	0	0	0	0	0
-5	0.2916	0.0950	0.1609	0.0704	0.2112	0.1709	774151	6139688	4144347	285239	0	0	0	0	0	0
-4	0.2913	0.0960	0.1607	0.0703	0.2109	0.1708	774151	6139688	4144347	285239	0	0	0	0	0	0
-3	0.2910	0.0970	0.1605	0.0702	0.2107	0.1706	774151	6139688	4144347	285239	0	0	0	0	0	0
-2	0.2906	0.0980	0.1604	0.0702	0.2105	0.1704	774151	6139661	4144315	285298	0	0	0	0	0	0
-1	0.2903	0.0990	0.1602	0.0701	0.2102	0.1702	774151	6139661	4144315	285298	0	0	0	0	0	0
0	**0.2900**	**0.1000**	**0.1600**	**0.0700**	**0.2100**	**0.1700**	**774151**	**6139865**	**4144171**	**285238**	**0**	**-**	**-**	**-**	**-**	**-**
1	0.2897	0.1010	0.1598	0.0699	0.2098	0.1698	774151	6139849	4144187	285238	0	0	0	0	0	0
2	0.2894	0.1020	0.1596	0.0698	0.2095	0.1696	774151	6139849	4144187	285238	0	0	0	0	0	0
3	0.2890	0.1030	0.1595	0.0698	0.2093	0.1694	774151	6139849	4144187	285238	0	0	0	0	0	0
4	0.2887	0.1040	0.1593	0.0697	0.2091	0.1692	774151	6139849	4144187	285238	0	0	0	0	0	0
5	0.2884	0.1050	0.1591	0.0696	0.2088	0.1691	774151	6140131	4144327	284816	0	0	0	0	0	0
6	0.2881	0.1060	0.1589	0.0695	0.2086	0.1689	774151	6140131	4144327	284816	0	0	0	0	0	0
7	0.2877	0.1070	0.1588	0.0695	0.2084	0.1687	774151	6140131	4144327	284816	0	0	0	0	0	0
8	0.2874	0.1080	0.1586	0.0694	0.2081	0.1685	774151	6140131	4144327	284816	0	0	0	0	0	0
9	0.2871	0.1090	0.1584	0.0693	0.2079	0.1683	774151	6140813	4143761	284700	0	0	0	0	0	0
10	0.2868	0.1100	0.1582	0.0692	0.2077	0.1681	774151	6140813	4143761	284700	0	0	0	0	0	0
11	0.2865	0.1110	0.1580	0.0691	0.2074	0.1679	774151	6140813	4143761	284700	0	0	0	0	0	0
12	0.2861	0.1120	0.1579	0.0691	0.2072	0.1677	774151	6140809	4147690	280775	0	0	0	0	-2	0
13	0.2858	0.1130	0.1577	0.0690	0.2070	0.1675	774151	6140809	4147690	280775	0	0	0	0	-2	0
14	0.2855	0.1140	0.1575	0.0689	0.2067	0.1674	774151	6140809	4147690	280775	0	0	0	0	-2	0
15	0.2852	0.1150	0.1573	0.0688	0.2065	0.1672	774151	6140809	4147690	280775	0	0	0	0	-2	0
16	0.2848	0.1160	0.1572	0.0688	0.2063	0.1670	774151	6141188	4147275	280811	0	0	0	0	-2	0
17	0.2845	0.1170	0.1570	0.0687	0.2060	0.1668	774151	6141188	4147275	280811	0	0	0	0	-2	0
18	0.2842	0.1180	0.1568	0.0686	0.2058	0.1666	774151	6141188	4147275	280811	0	0	0	0	-2	0
19	0.2839	0.1190	0.1566	0.0685	0.2056	0.1664	774151	6141188	4147275	280811	0	0	0	0	-2	0
20	0.2836	0.1200	0.1564	0.0684	0.2053	0.1662	774151	6141188	4147097	280989	0	0	0	0	-1	0

Table 45. Summary table showing changes in cell cost values when the weight of criterion C3 – "Minimise a number of by-pass crossings with rivers with high-order drainage" is changed

%	Criterion weight values						Total number of cells in every cost class					Percentage change (%)				
PC	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
-20	0.3010	0.1038	0.1280	0.0727	0.2180	0.1765	774151	6119188	4145005	305081	0	0	0	0	7	0
-19	0.3005	0.1036	0.1296	0.0725	0.2176	0.1762	774151	6119199	4145051	305024	0	0	0	0	7	0
-18	0.2999	0.1034	0.1312	0.0724	0.2172	0.1758	774151	6119199	4145051	305024	0	0	0	0	7	0
-17	0.2994	0.1032	0.1328	0.0723	0.2168	0.1755	774151	6119199	4145051	305024	0	0	0	0	7	0
-16	0.2988	0.1030	0.1344	0.0721	0.2164	0.1752	774151	6133296	4138186	297792	0	0	0	0	4	0
-15	0.2983	0.1029	0.1360	0.0720	0.2160	0.1749	774151	6133296	4138186	297792	0	0	0	0	4	0
-14	0.2977	0.1027	0.1376	0.0719	0.2156	0.1745	774151	6132877	4138302	298095	0	0	0	0	5	0
-13	0.2972	0.1025	0.1392	0.0717	0.2152	0.1742	774151	6132806	4138373	298095	0	0	0	0	5	0
-12	0.2966	0.1023	0.1408	0.0716	0.2148	0.1739	774151	6132806	4138373	298095	0	0	0	0	5	0
-11	0.2961	0.1021	0.1424	0.0715	0.2144	0.1736	774151	6132806	4138373	298095	0	0	0	0	5	0
-10	0.2955	0.1019	0.1440	0.0713	0.2140	0.1732	774151	6132855	4138605	297814	0	0	0	0	4	0
-9	0.2950	0.1017	0.1456	0.0712	0.2136	0.1729	774151	6132855	4138605	297814	0	0	0	0	4	0
-8	0.2944	0.1015	0.1472	0.0711	0.2132	0.1726	774151	6132855	4138605	297814	0	0	0	0	4	0
-7	0.2939	0.1013	0.1488	0.0709	0.2128	0.1723	774151	6132855	4134689	301730	0	0	0	0	6	0
-6	0.2933	0.1011	0.1504	0.0708	0.2124	0.1719	774151	6132855	4134689	301730	0	0	0	0	6	0
-5	0.2928	0.1010	0.1520	0.0707	0.2120	0.1716	774151	6140156	4143963	285155	0	0	0	0	0	0
-4	0.2922	0.1008	0.1536	0.0705	0.2116	0.1713	774151	6140156	4143963	285155	0	0	0	0	0	0
-3	0.2917	0.1006	0.1552	0.0704	0.2112	0.1710	774151	6140156	4143963	285155	0	0	0	0	0	0
-2	0.2911	0.1004	0.1568	0.0703	0.2108	0.1706	774151	6139847	4144161	285266	0	0	0	0	0	0
-1	0.2906	0.1002	0.1584	0.0701	0.2104	0.1703	774151	6139652	4144356	285266	0	0	0	0	0	0
0	**0.2900**	**0.1000**	**0.1600**	**0.0700**	**0.2100**	**0.1700**	**774151**	**6139865**	**4144171**	**285238**	**0**	**-**	**-**	**-**	**-**	**-**
1	0.2894	0.0998	0.1616	0.0699	0.2096	0.1697	774151	6139865	4144139	285270	0	0	0	0	0	0
2	0.2889	0.0996	0.1632	0.0697	0.2092	0.1694	774151	6139865	4144139	285270	0	0	0	0	0	0
3	0.2883	0.0994	0.1648	0.0696	0.2088	0.1690	774151	6138021	4145983	285270	0	0	0	0	0	0
4	0.2878	0.0992	0.1664	0.0695	0.2084	0.1687	774151	6138021	4145983	285270	0	0	0	0	0	0
5	0.2872	0.0990	0.1680	0.0693	0.2080	0.1684	774151	6138021	4145983	285270	0	0	0	0	0	0
6	0.2867	0.0989	0.1696	0.0692	0.2076	0.1681	774151	6138272	4144929	285951	122	0	0	0	0	0
7	0.2861	0.0987	0.1712	0.0691	0.2072	0.1677	774151	6138272	4144929	285951	122	0	0	0	0	0
8	0.2856	0.0985	0.1728	0.0689	0.2068	0.1674	774151	6137634	4145324	286194	122	0	0	0	0	0
9	0.2850	0.0983	0.1744	0.0688	0.2064	0.1671	774151	6137634	4145324	286194	122	0	0	0	0	0
10	0.2845	0.0981	0.1760	0.0687	0.2060	0.1668	774151	6137634	4145324	286194	122	0	0	0	0	0
11	0.2839	0.0979	0.1776	0.0685	0.2056	0.1664	774151	6125029	4157929	286194	122	0	0	0	0	0
12	0.2834	0.0977	0.1792	0.0684	0.2052	0.1661	774151	6125029	4157929	286194	122	0	0	0	0	0
13	0.2828	0.0975	0.1808	0.0683	0.2048	0.1658	774151	6125029	4157751	286372	122	0	0	0	0	0
14	0.2823	0.0973	0.1824	0.0681	0.2044	0.1655	774151	6121816	4158338	288998	122	0	0	0	1	0
15	0.2817	0.0971	0.1840	0.0680	0.2040	0.1651	774151	6121816	4158338	288998	122	0	0	0	1	0
16	0.2812	0.0970	0.1856	0.0679	0.2036	0.1648	774151	6161087	4208358	199707	122	0	0	2	-30	0
17	0.2806	0.0968	0.1872	0.0677	0.2032	0.1645	774151	6161087	4208358	199707	122	0	0	2	-30	0
18	0.2801	0.0966	0.1888	0.0676	0.2028	0.1642	774151	6161087	4208356	199709	122	0	0	2	-30	0
19	0.2795	0.0964	0.1904	0.0675	0.2024	0.1638	774151	6161080	4208363	199709	122	0	0	2	-30	0
20	0.2790	0.0962	0.1920	0.0673	0.2020	0.1635	774151	6161087	4208356	199709	122	0	0	2	-30	0

Table 46. Summary table showing changes in cell cost values when the weight of criterion C4 – "Maximise distance to flooding areas" is changed

%	Criterion weight values						Total number of cells in every cost class					Percentage change (%)				
PC	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
-20	0.2944	0.1015	0.1624	0.0560	0.2132	0.1726	774151	6134903	4132565	301806	0	0	0	0	6	0
-19	0.2941	0.1014	0.1623	0.0567	0.2130	0.1724	774151	6134910	4132558	301806	0	0	0	0	6	0
-18	0.2939	0.1014	0.1622	0.0574	0.2128	0.1723	774151	6134910	4132558	301806	0	0	0	0	6	0
-17	0.2937	0.1013	0.1620	0.0581	0.2127	0.1722	774151	6134895	4132534	301845	0	0	0	0	6	0
-16	0.2935	0.1012	0.1619	0.0588	0.2125	0.1720	774151	6134895	4132534	301845	0	0	0	0	6	0
-15	0.2933	0.1011	0.1618	0.0595	0.2124	0.1719	774151	6134895	4132534	301845	0	0	0	0	6	0
-14	0.2931	0.1011	0.1617	0.0602	0.2122	0.1718	774151	6134895	4132534	301845	0	0	0	0	6	0
-13	0.2928	0.1010	0.1616	0.0609	0.2121	0.1717	774151	6140680	4143430	285164	0	0	0	0	0	0
-12	0.2926	0.1009	0.1614	0.0616	0.2119	0.1715	774151	6140687	4143423	285164	0	0	0	0	0	0
-11	0.2924	0.1008	0.1613	0.0623	0.2117	0.1714	774151	6140687	4143423	285164	0	0	0	0	0	0
-10	0.2922	0.1008	0.1612	0.0630	0.2116	0.1713	774151	6140687	4143423	285164	0	0	0	0	0	0
-9	0.2920	0.1007	0.1611	0.0637	0.2114	0.1712	774151	6140687	4143423	285164	0	0	0	0	0	0
-8	0.2917	0.1006	0.1610	0.0644	0.2113	0.1710	774151	6140057	4144052	285165	0	0	0	0	0	0
-7	0.2915	0.1005	0.1608	0.0651	0.2111	0.1709	774151	6140057	4144052	285165	0	0	0	0	0	0
-6	0.2913	0.1005	0.1607	0.0658	0.2109	0.1708	774151	6139803	4144289	285182	0	0	0	0	0	0
-5	0.2911	0.1004	0.1606	0.0665	0.2108	0.1706	774151	6139810	4144282	285182	0	0	0	0	0	0
-4	0.2909	0.1003	0.1605	0.0672	0.2106	0.1705	774151	6139783	4144250	285241	0	0	0	0	0	0
-3	0.2907	0.1002	0.1604	0.0679	0.2105	0.1704	774151	6139783	4144250	285241	0	0	0	0	0	0
-2	0.2904	0.1002	0.1602	0.0686	0.2103	0.1703	774151	6139783	4144250	285241	0	0	0	0	0	0
-1	0.2902	0.1001	0.1601	0.0693	0.2102	0.1701	774151	6139783	4144250	285241	0	0	0	0	0	0
0	**0.2900**	**0.1000**	**0.1600**	**0.0700**	**0.2100**	**0.1700**	**774151**	**6139865**	**4144171**	**285238**	**0**	**-**	**-**	**-**	**-**	**-**
1	0.2898	0.0999	0.1599	0.0707	0.2098	0.1699	774151	6139743	4144236	285295	0	0	0	0	0	0
2	0.2896	0.0998	0.1598	0.0714	0.2097	0.1697	774151	6139750	4144229	285295	0	0	0	0	0	0
3	0.2893	0.0998	0.1596	0.0721	0.2095	0.1696	774151	6139750	4144229	285295	0	0	0	0	0	0
4	0.2891	0.0997	0.1595	0.0728	0.2094	0.1695	774151	6139750	4144229	285295	0	0	0	0	0	0
5	0.2889	0.0996	0.1594	0.0735	0.2092	0.1694	774151	6138114	4145849	285311	0	0	0	0	0	0
6	0.2887	0.0995	0.1593	0.0742	0.2091	0.1692	774151	6138114	4145849	285311	0	0	0	0	0	0
7	0.2885	0.0995	0.1592	0.0749	0.2089	0.1691	774151	6138396	4145989	284889	0	0	0	0	0	0
8	0.2883	0.0994	0.1590	0.0756	0.2087	0.1690	774151	6138389	4145996	284889	0	0	0	0	0	0
9	0.2880	0.0993	0.1589	0.0763	0.2086	0.1688	774151	6138158	4146123	284993	0	0	0	0	0	0
10	0.2878	0.0992	0.1588	0.0770	0.2084	0.1687	774151	6138158	4146123	284993	0	0	0	0	0	0
11	0.2876	0.0992	0.1587	0.0777	0.2083	0.1686	774151	6138158	4146123	284993	0	0	0	0	0	0
12	0.2874	0.0991	0.1586	0.0784	0.2081	0.1685	774151	6138158	4146123	284993	0	0	0	0	0	0
13	0.2872	0.0990	0.1584	0.0791	0.2079	0.1683	774151	6138158	4146123	284993	0	0	0	0	0	0
14	0.2869	0.0989	0.1583	0.0798	0.2078	0.1682	774151	6122905	4153027	293220	122	0	0	0	3	0
15	0.2867	0.0989	0.1582	0.0805	0.2076	0.1681	774151	6122898	4153034	293220	122	0	0	0	3	0
16	0.2865	0.0988	0.1581	0.0812	0.2075	0.1680	774151	6122905	4153027	293220	122	0	0	0	3	0
17	0.2863	0.0987	0.1580	0.0819	0.2073	0.1678	774151	6122905	4153027	293220	122	0	0	0	3	0
18	0.2861	0.0986	0.1578	0.0826	0.2072	0.1677	774151	6122905	4153027	293220	122	0	0	0	3	0
19	0.2859	0.0986	0.1577	0.0833	0.2070	0.1676	774151	6122905	4153027	293220	122	0	0	0	3	0
20	0.2856	0.0985	0.1576	0.0840	0.2068	0.1674	774151	6122905	4153027	293220	122	0	0	0	3	0

Table 47. Summary table showing changes in cell cost values when the weight of criterion C5 – "Maximise geological construction suitability" is changed

%	Criterion weight values						Total number of cells in every cost class					Percentage change (%)				
PC	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
-20	0.3054	0.1053	0.1685	0.0737	0.1680	0.1790	774151	6165719	4121326	282107	122	0	0	-1	-1	0
-19	0.3046	0.1051	0.1681	0.0735	0.1701	0.1786	774151	6165719	4121504	281929	122	0	0	-1	-1	0
-18	0.3039	0.1048	0.1677	0.0733	0.1722	0.1781	774151	6165719	4121504	281929	122	0	0	-1	-1	0
-17	0.3031	0.1045	0.1672	0.0732	0.1743	0.1777	774151	6163901	4123322	281929	122	0	0	-1	-1	0
-16	0.3023	0.1043	0.1668	0.0730	0.1764	0.1772	774151	6163901	4123322	281929	122	0	0	-1	-1	0
-15	0.3016	0.1040	0.1664	0.0728	0.1785	0.1768	774151	6171628	4115846	281678	122	0	1	-1	-1	0
-14	0.3008	0.1037	0.1660	0.0726	0.1806	0.1763	774151	6171628	4115846	281678	122	0	1	-1	-1	0
-13	0.3000	0.1035	0.1655	0.0724	0.1827	0.1759	774151	6171628	4115846	281678	122	0	1	-1	-1	0
-12	0.2993	0.1032	0.1651	0.0722	0.1848	0.1754	774151	6171628	4115846	281678	122	0	1	-1	-1	0
-11	0.2985	0.1029	0.1647	0.0720	0.1869	0.1750	774151	6140635	4142613	285904	122	0	0	0	0	0
-10	0.2977	0.1027	0.1643	0.0719	0.1890	0.1745	774151	6140635	4142613	285904	122	0	0	0	0	0
-9	0.2969	0.1024	0.1638	0.0717	0.1911	0.1741	774151	6140635	4142700	285817	122	0	0	0	0	0
-8	0.2962	0.1021	0.1634	0.0715	0.1932	0.1736	774151	6140635	4142700	285817	122	0	0	0	0	0
-7	0.2954	0.1019	0.1630	0.0713	0.1953	0.1732	774151	6140532	4142909	285711	122	0	0	0	0	0
-6	0.2946	0.1016	0.1626	0.0711	0.1974	0.1727	774151	6140532	4142909	285711	122	0	0	0	0	0
-5	0.2939	0.1013	0.1621	0.0709	0.1995	0.1723	774151	6140532	4142909	285711	122	0	0	0	0	0
-4	0.2931	0.1011	0.1617	0.0707	0.2016	0.1718	774151	6140532	4142909	285711	122	0	0	0	0	0
-3	0.2923	0.1008	0.1613	0.0706	0.2037	0.1714	774151	6139858	4144146	285270	0	0	0	0	0	0
-2	0.2915	0.1005	0.1609	0.0704	0.2058	0.1709	774151	6139858	4144146	285270	0	0	0	0	0	0
-1	0.2908	0.1003	0.1604	0.0702	0.2079	0.1705	774151	6139858	4144146	285270	0	0	0	0	0	0
0	**0.2900**	**0.1000**	**0.1600**	**0.0700**	**0.2100**	**0.1700**	**774151**	**6139865**	**4144171**	**285238**	**0**	**-**	**-**	**-**	**-**	**-**
1	0.2892	0.0997	0.1596	0.0698	0.2121	0.1695	774151	6139767	4144266	285241	0	0	0	0	0	0
2	0.2885	0.0995	0.1591	0.0696	0.2142	0.1691	774151	6139767	4144266	285241	0	0	0	0	0	0
3	0.2877	0.0992	0.1587	0.0694	0.2163	0.1686	774151	6139767	4144266	285241	0	0	0	0	0	0
4	0.2869	0.0989	0.1583	0.0693	0.2184	0.1682	774151	6138472	4145624	285178	0	0	0	0	0	0
5	0.2861	0.0987	0.1579	0.0691	0.2205	0.1677	774151	6138472	4145624	285178	0	0	0	0	0	0
6	0.2854	0.0984	0.1574	0.0689	0.2226	0.1673	774151	6138357	4145714	285203	0	0	0	0	0	0
7	0.2846	0.0981	0.1570	0.0687	0.2247	0.1668	774151	6138472	4145624	285178	0	0	0	0	0	0
8	0.2838	0.0979	0.1566	0.0685	0.2268	0.1664	774151	6132170	4134924	302180	0	0	0	0	6	0
9	0.2831	0.0976	0.1562	0.0683	0.2289	0.1659	774151	6132170	4134924	302180	0	0	0	0	6	0
10	0.2823	0.0973	0.1557	0.0681	0.2310	0.1655	774151	6102952	4163174	303148	0	0	-1	0	6	0
11	0.2815	0.0971	0.1553	0.0680	0.2331	0.1650	774151	6101734	4164712	302828	0	0	-1	0	6	0
12	0.2807	0.0968	0.1549	0.0678	0.2352	0.1646	774151	6101734	4164712	302828	0	0	-1	0	6	0
13	0.2800	0.0965	0.1545	0.0676	0.2373	0.1641	774151	6093174	4173272	302828	0	0	-1	1	6	0
14	0.2792	0.0963	0.1540	0.0674	0.2394	0.1637	774151	6093174	4173272	302828	0	0	-1	1	6	0
15	0.2784	0.0960	0.1536	0.0672	0.2415	0.1632	774151	6090377	4176026	302871	0	0	-1	1	6	0
16	0.2777	0.0957	0.1532	0.0670	0.2436	0.1628	774151	6090377	4176026	302871	0	0	-1	1	6	0
17	0.2769	0.0955	0.1528	0.0668	0.2457	0.1623	774151	6090377	4176026	302871	0	0	-1	1	6	0
18	0.2761	0.0952	0.1523	0.0667	0.2478	0.1619	774151	6089213	4179604	300457	0	0	-1	1	5	0
19	0.2754	0.0949	0.1519	0.0665	0.2499	0.1614	774151	6089213	4179604	300457	0	0	-1	1	5	0
20	0.2746	0.0947	0.1515	0.0663	0.2520	0.1610	774151	6089213	4179604	300457	0	0	-1	1	5	0

Table 48. Summary table showing changes in cell cost values when the weight of criterion C6 – "Maximise soil construction suitability" is changed

%	Criterion weight values						Total number of cells in every cost class					Percentage change (%)				
PC	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
-20	0.3019	0.1041	0.1666	0.0729	0.2186	0.1360	774151	6173778	4117231	278265	0	0	1	-1	-2	0
-19	0.3013	0.1039	0.1662	0.0727	0.2182	0.1377	774151	6173777	4117234	278263	0	0	1	-1	-2	0
-18	0.3007	0.1037	0.1659	0.0726	0.2177	0.1394	774151	6173777	4117234	278263	0	0	1	-1	-2	0
-17	0.3001	0.1035	0.1656	0.0724	0.2173	0.1411	774151	6173777	4117234	278263	0	0	1	-1	-2	0
-16	0.2995	0.1033	0.1652	0.0723	0.2169	0.1428	774151	6141622	4145306	282346	0	0	0	0	-1	0
-15	0.2989	0.1031	0.1649	0.0722	0.2165	0.1445	774151	6141622	4145306	282346	0	0	0	0	-1	0
-14	0.2983	0.1029	0.1646	0.0720	0.2160	0.1462	774151	6141622	4145306	282346	0	0	0	0	-1	0
-13	0.2977	0.1027	0.1643	0.0719	0.2156	0.1479	774151	6140769	4143784	284721	0	0	0	0	0	0
-12	0.2971	0.1025	0.1639	0.0717	0.2152	0.1496	774151	6140769	4143784	284721	0	0	0	0	0	0
-11	0.2965	0.1023	0.1636	0.0716	0.2147	0.1513	774151	6140769	4143784	284721	0	0	0	0	0	0
-10	0.2959	0.1020	0.1633	0.0714	0.2143	0.1530	774151	6138750	4145709	284815	0	0	0	0	0	0
-9	0.2953	0.1018	0.1629	0.0713	0.2139	0.1547	774151	6138750	4145709	284815	0	0	0	0	0	0
-8	0.2948	0.1016	0.1626	0.0711	0.2134	0.1564	774151	6138750	4145709	284815	0	0	0	0	0	0
-7	0.2942	0.1014	0.1623	0.0710	0.2130	0.1581	774151	6138750	4145706	284818	0	0	0	0	0	0
-6	0.2936	0.1012	0.1620	0.0709	0.2126	0.1598	774151	6138750	4145706	284818	0	0	0	0	0	0
-5	0.2930	0.1010	0.1616	0.0707	0.2122	0.1615	774151	6139960	4144128	285186	0	0	0	0	0	0
-4	0.2924	0.1008	0.1613	0.0706	0.2117	0.1632	774151	6139960	4144128	285186	0	0	0	0	0	0
-3	0.2918	0.1006	0.1610	0.0704	0.2113	0.1649	774151	6139960	4144128	285186	0	0	0	0	0	0
-2	0.2912	0.1004	0.1607	0.0703	0.2109	0.1666	774151	6139652	4144324	285298	0	0	0	0	0	0
-1	0.2906	0.1002	0.1603	0.0701	0.2104	0.1683	774151	6139652	4144324	285298	0	0	0	0	0	0
0	**0.2900**	**0.1000**	**0.1600**	**0.0700**	**0.2100**	**0.1700**	**774151**	**6139865**	**4144171**	**285238**	**0**	-	-	-	-	-
1	0.2894	0.0998	0.1597	0.0699	0.2096	0.1717	774151	6139858	4144178	285238	0	0	0	0	0	0
2	0.2888	0.0996	0.1593	0.0697	0.2091	0.1734	774151	6139858	4144178	285238	0	0	0	0	0	0
3	0.2882	0.0994	0.1590	0.0696	0.2087	0.1751	774151	6139838	4144198	285238	0	0	0	0	0	0
4	0.2876	0.0992	0.1587	0.0694	0.2083	0.1768	774151	6139838	4144198	285238	0	0	0	0	0	0
5	0.2870	0.0990	0.1584	0.0693	0.2078	0.1785	774151	6139838	4144198	285238	0	0	0	0	0	0
6	0.2864	0.0988	0.1580	0.0691	0.2074	0.1802	774151	6138765	4145129	285380	0	0	0	0	0	0
7	0.2858	0.0986	0.1577	0.0690	0.2070	0.1819	774151	6138765	4145129	285380	0	0	0	0	0	0
8	0.2852	0.0984	0.1574	0.0689	0.2066	0.1836	774151	6124643	4152011	292620	0	0	0	0	3	0
9	0.2847	0.0982	0.1571	0.0687	0.2061	0.1853	774151	6124643	4152011	292620	0	0	0	0	3	0
10	0.2841	0.0980	0.1567	0.0686	0.2057	0.1870	774151	6124643	4152011	292620	0	0	0	0	3	0
11	0.2835	0.0977	0.1564	0.0684	0.2053	0.1887	774151	6107071	4151659	310422	122	0	-1	0	9	0
12	0.2829	0.0975	0.1561	0.0683	0.2048	0.1904	774151	6107071	4151659	310422	122	0	-1	0	9	0
13	0.2823	0.0973	0.1557	0.0681	0.2044	0.1921	774151	6107071	4151659	310422	122	0	-1	0	9	0
14	0.2817	0.0971	0.1554	0.0680	0.2040	0.1938	774151	6107071	4151659	310422	122	0	-1	0	9	0
15	0.2811	0.0969	0.1551	0.0678	0.2035	0.1955	774151	6107071	4151659	310422	122	0	-1	0	9	0
16	0.2805	0.0967	0.1548	0.0677	0.2031	0.1972	774151	6107041	4152014	310097	122	0	-1	0	9	0
17	0.2799	0.0965	0.1544	0.0676	0.2027	0.1989	774151	6107041	4152014	310097	122	0	-1	0	9	0
18	0.2793	0.0963	0.1541	0.0674	0.2023	0.2006	774151	6106962	4152036	310154	122	0	-1	0	9	0
19	0.2787	0.0961	0.1538	0.0673	0.2018	0.2023	774151	6106962	4152036	310154	122	0	-1	0	9	0
20	0.2781	0.0959	0.1534	0.0671	0.2014	0.2040	774151	6106962	4152036	310154	122	0	-1	0	9	0

Table 49. Summary table showing changes in cell cost values when the weight of criterion C7 – "Maximise distance to natural protected areas" is changed

%	Criterion weight values				Total number of cells in every cost class					Percentage change (%)				
PC	**C7**	**C8**	**C9**	**C10**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
-20	0.2320	0.4435	0.2055	0.1190	857205	6348910	3828988	307018	1304	0	0	0	7	99
-19	0.2349	0.4418	0.2047	0.1185	857205	6348910	3828988	307018	1304	0	0	0	7	99
-18	0.2378	0.4401	0.2040	0.1181	857205	6372933	3811029	300954	1304	0	0	-1	5	99
-17	0.2407	0.4385	0.2032	0.1176	857205	6372933	3811029	300954	1304	0	0	-1	5	99
-16	0.2436	0.4368	0.2024	0.1172	857205	6372933	3811029	300954	1304	0	0	-1	5	99
-15	0.2465	0.4351	0.2016	0.1167	857205	6372933	3811029	300954	1304	0	0	-1	5	99
-14	0.2494	0.4334	0.2009	0.1163	857205	6372933	3811029	300954	1304	0	0	-1	5	99
-13	0.2523	0.4318	0.2001	0.1158	857205	6372933	3823579	289059	649	0	0	0	1	-1
-12	0.2552	0.4301	0.1993	0.1154	857205	6372933	3823577	289061	649	0	0	0	1	-1
-11	0.2581	0.4284	0.1985	0.1149	857205	6371975	3824537	289059	649	0	0	0	1	-1
-10	0.2610	0.4267	0.1978	0.1145	857205	6371986	3825364	288221	649	0	0	0	1	-1
-9	0.2639	0.4251	0.1970	0.1140	857205	6371986	3825362	288223	649	0	0	0	1	-1
-8	0.2668	0.4234	0.1962	0.1136	857205	6371986	3825364	288221	649	0	0	0	1	-1
-7	0.2697	0.4217	0.1954	0.1131	857205	6371999	3827385	286187	649	0	0	0	0	-1
-6	0.2726	0.4200	0.1947	0.1127	857205	6371999	3827385	286187	649	0	0	0	0	-1
-5	0.2755	0.4184	0.1939	0.1122	857205	6371999	3827385	286187	649	0	0	0	0	-1
-4	0.2784	0.4167	0.1931	0.1118	857205	6367726	3830928	286911	655	0	0	0	0	0
-3	0.2813	0.4150	0.1923	0.1113	857205	6368818	3831945	284802	655	0	0	0	0	0
-2	0.2842	0.4133	0.1916	0.1109	857205	6368818	3831945	284802	655	0	0	0	0	0
-1	0.2871	0.4117	0.1908	0.1104	857205	6368818	3830886	285861	655	0	0	0	0	0
0	**0.2900**	**0.4100**	**0.1900**	**0.1100**	**857205**	**6368818**	**3830886**	**285861**	**655**	**-**	**-**	**-**	**-**	**-**
1	0.2929	0.4083	0.1892	0.1096	857205	6368818	3830886	285861	655	0	0	0	0	0
2	0.2958	0.4067	0.1884	0.1091	857205	6368818	3830886	285861	655	0	0	0	0	0
3	0.2987	0.4050	0.1877	0.1087	857205	6420472	3795380	269565	803	0	1	-1	-6	23
4	0.3016	0.4033	0.1869	0.1082	857205	6420472	3795380	269565	803	0	1	-1	-6	23
5	0.3045	0.4016	0.1861	0.1078	857205	6420472	3795378	269567	803	0	1	-1	-6	23
6	0.3074	0.4000	0.1853	0.1073	857205	6423254	3809396	252767	803	0	1	-1	-12	23
7	0.3103	0.3983	0.1846	0.1069	857205	6423254	3809396	252767	803	0	1	-1	-12	23
8	0.3132	0.3966	0.1838	0.1064	857205	6423254	3809394	252769	803	0	1	-1	-12	23
9	0.3161	0.3949	0.1830	0.1060	857205	6423254	3809396	252767	803	0	1	-1	-12	23
10	0.3190	0.3933	0.1822	0.1055	857205	6487704	3773818	223895	803	0	2	-1	-22	23
11	0.3219	0.3916	0.1815	0.1051	857205	6487704	3773818	223895	803	0	2	-1	-22	23
12	0.3248	0.3899	0.1807	0.1046	857205	6487704	3773818	223895	803	0	2	-1	-22	23
13	0.3277	0.3882	0.1799	0.1042	857205	6487704	3773818	223895	803	0	2	-1	-22	23
14	0.3306	0.3866	0.1791	0.1037	857205	6487704	3773818	223895	803	0	2	-1	-22	23
15	0.3335	0.3849	0.1784	0.1033	857205	6487704	3774159	223554	803	0	2	-1	-22	23
16	0.3364	0.3832	0.1776	0.1028	857205	6487704	3774159	223554	803	0	2	-1	-22	23
17	0.3393	0.3815	0.1768	0.1024	857205	6487704	3774159	223554	803	0	2	-1	-22	23
18	0.3422	0.3799	0.1760	0.1019	857205	6487704	3774159	223554	803	0	2	-1	-22	23
19	0.3451	0.3782	0.1753	0.1015	857205	6487704	3774160	223553	803	0	2	-1	-22	23
20	0.3480	0.3765	0.1745	0.1010	857205	6487704	3774160	223553	803	0	2	-1	-22	23

Table 50. Summary table showing changes in cell cost values when the weight of criterion C8 – "Maximise distance to fragile water streams" is changed

%	Criterion weight values				Total number of cells in every cost class					Percentage change (%)				
PC	**C7**	**C8**	**C9**	**C10**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
-20	0.3303	0.3280	0.2164	0.1253	857205	6425775	3801631	258159	655	0	1	-1	-10	0
-19	0.3283	0.3321	0.2151	0.1245	857205	6425775	3801631	258159	655	0	1	-1	-10	0
-18	0.3263	0.3362	0.2138	0.1238	857205	6425775	3801631	258159	655	0	1	-1	-10	0
-17	0.3243	0.3403	0.2124	0.1230	857205	6425775	3801631	258159	655	0	1	-1	-10	0
-16	0.3222	0.3444	0.2111	0.1222	857205	6425775	3801631	258159	655	0	1	-1	-10	0
-15	0.3202	0.3485	0.2098	0.1215	857205	6425775	3800882	258908	655	0	1	-1	-9	0
-14	0.3182	0.3526	0.2085	0.1207	857205	6425775	3800882	258908	655	0	1	-1	-9	0
-13	0.3162	0.3567	0.2072	0.1199	857205	6424755	3801804	259006	655	0	1	-1	-9	0
-12	0.3142	0.3608	0.2058	0.1192	857205	6424755	3801804	259006	655	0	1	-1	-9	0
-11	0.3122	0.3649	0.2045	0.1184	857205	6424755	3801804	259006	655	0	1	-1	-9	0
-10	0.3102	0.3690	0.2032	0.1176	857205	6424755	3801804	259006	655	0	1	-1	-9	0
-9	0.3081	0.3731	0.2019	0.1169	857205	6424755	3801804	259006	655	0	1	-1	-9	0
-8	0.3061	0.3772	0.2006	0.1161	857205	6424862	3802535	258168	655	0	1	-1	-10	0
-7	0.3041	0.3813	0.1992	0.1154	857205	6424862	3802623	258080	655	0	1	-1	-10	0
-6	0.3021	0.3854	0.1979	0.1146	857205	6425954	3803640	255971	655	0	1	-1	-10	0
-5	0.3001	0.3895	0.1966	0.1138	857205	6425954	3803640	255971	655	0	1	-1	-10	0
-4	0.2981	0.3936	0.1953	0.1131	857205	6424791	3775345	285429	655	0	1	-1	0	0
-3	0.2960	0.3977	0.1940	0.1123	857205	6424791	3775345	285429	655	0	1	-1	0	0
-2	0.2940	0.4018	0.1926	0.1115	857205	6368818	3830886	285861	655	0	0	0	0	0
-1	0.2920	0.4059	0.1913	0.1108	857205	6368818	3830886	285861	655	0	0	0	0	0
0	**0.2900**	**0.4100**	**0.1900**	**0.1100**	**857205**	**6368818**	**3830886**	**285861**	**655**	**-**	**-**	**-**	**-**	**-**
1	0.2880	0.4141	0.1887	0.1092	857205	6368818	3830884	285863	655	0	0	0	0	0
2	0.2860	0.4182	0.1874	0.1085	857205	6368818	3830884	285863	655	0	0	0	0	0
3	0.2840	0.4223	0.1860	0.1077	857205	6368479	3832140	284946	655	0	0	0	0	0
4	0.2819	0.4264	0.1847	0.1069	857205	6368479	3832140	284946	655	0	0	0	0	0
5	0.2799	0.4305	0.1834	0.1062	857205	6367173	3834318	284080	649	0	0	0	-1	-1
6	0.2779	0.4346	0.1821	0.1054	857205	6367173	3834318	284080	649	0	0	0	-1	-1
7	0.2759	0.4387	0.1808	0.1046	857205	6367173	3834318	284080	649	0	0	0	-1	-1
8	0.2739	0.4428	0.1794	0.1039	857205	6367173	3834318	284080	649	0	0	0	-1	-1
9	0.2719	0.4469	0.1781	0.1031	857205	6373091	3828400	284080	649	0	0	0	-1	-1
10	0.2698	0.4510	0.1768	0.1024	857205	6373091	3828400	284080	649	0	0	0	-1	-1
11	0.2678	0.4551	0.1755	0.1016	857205	6373091	3828400	284080	649	0	0	0	-1	-1
12	0.2658	0.4592	0.1742	0.1008	857205	6373091	3828400	284080	649	0	0	0	-1	-1
13	0.2638	0.4633	0.1728	0.1001	857205	6373091	3829714	282766	649	0	0	0	-1	-1
14	0.2618	0.4674	0.1715	0.0993	857205	6373091	3829714	282766	649	0	0	0	-1	-1
15	0.2598	0.4715	0.1702	0.0985	857205	6373091	3829714	282766	649	0	0	0	-1	-1
16	0.2578	0.4756	0.1689	0.0978	857205	6373091	3829714	282766	649	0	0	0	-1	-1
17	0.2557	0.4797	0.1676	0.0970	857205	6405863	3825789	253919	649	0	1	0	-11	-1
18	0.2537	0.4838	0.1662	0.0962	857205	6405244	3826405	253922	649	0	1	0	-11	-1
19	0.2517	0.4879	0.1649	0.0955	857205	6405244	3826405	253922	649	0	1	0	-11	-1
20	0.2497	0.4920	0.1636	0.0947	857205	6405244	3826405	253922	649	0	1	0	-11	-1

Table 51. Summary table showing changes in cell cost values when the weight of criterion C9 – "Maximise distance to surface waters – dams and ponds" is changed

%	Criterion weight values				Total number of cells in every cost class					Percentage change (%)				
PC	**C7**	**C8**	**C9**	**C10**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
-20	0.3036	0.4292	0.1520	0.1152	857205	6449941	3766314	268440	1525	0	1	-2	-6	133
-19	0.3029	0.4283	0.1539	0.1149	857205	6449490	3766614	268591	1525	0	1	-2	-6	133
-18	0.3022	0.4273	0.1558	0.1146	857205	6393381	3825835	266201	803	0	0	0	-7	23
-17	0.3016	0.4263	0.1577	0.1144	857205	6393381	3827008	265028	803	0	0	0	-7	23
-16	0.3009	0.4254	0.1596	0.1141	857205	6395165	3833088	257164	803	0	0	0	-10	23
-15	0.3002	0.4244	0.1615	0.1139	857205	6396487	3831789	257141	803	0	0	0	-10	23
-14	0.2995	0.4235	0.1634	0.1136	857205	6397140	3831888	256389	803	0	0	0	-10	23
-13	0.2988	0.4225	0.1653	0.1134	857205	6397140	3831888	256389	803	0	0	0	-10	23
-12	0.2982	0.4215	0.1672	0.1131	857205	6398551	3830489	256377	803	0	0	0	-10	23
-11	0.2975	0.4206	0.1691	0.1128	857205	6398551	3830489	256377	803	0	0	0	-10	23
-10	0.2968	0.4196	0.1710	0.1126	857205	6398551	3830489	256377	803	0	0	0	-10	23
-9	0.2961	0.4187	0.1729	0.1123	857205	6398551	3832912	253954	803	0	0	0	-11	23
-8	0.2954	0.4177	0.1748	0.1121	857205	6398551	3832912	253954	803	0	0	0	-11	23
-7	0.2948	0.4167	0.1767	0.1118	857205	6395769	3819452	270196	803	0	0	0	-5	23
-6	0.2941	0.4158	0.1786	0.1115	857205	6395769	3819452	270196	803	0	0	0	-5	23
-5	0.2934	0.4148	0.1805	0.1113	857205	6362997	3823377	299043	803	0	0	0	5	23
-4	0.2927	0.4138	0.1824	0.1110	857205	6362997	3823377	299043	803	0	0	0	5	23
-3	0.2920	0.4129	0.1843	0.1108	857205	6362997	3822821	299599	803	0	0	0	5	23
-2	0.2914	0.4119	0.1862	0.1105	857205	6363432	3822528	299457	803	0	0	0	5	23
-1	0.2907	0.4110	0.1881	0.1103	857205	6368818	3830884	285863	655	0	0	0	0	0
0	**0.2900**	**0.4100**	**0.1900**	**0.1100**	**857205**	**6368818**	**3830886**	**285861**	**655**	**-**	**-**	**-**	**-**	**-**
1	0.2893	0.4090	0.1919	0.1097	857205	6368818	3830886	285861	655	0	0	0	0	0
2	0.2886	0.4081	0.1938	0.1095	857205	6424791	3776404	284370	655	0	1	-1	-1	0
3	0.2880	0.4071	0.1957	0.1092	857205	6429617	3769469	286479	655	0	1	-2	0	0
4	0.2873	0.4062	0.1976	0.1090	857205	6429617	3769469	286479	655	0	1	-2	0	0
5	0.2866	0.4052	0.1995	0.1087	857205	6429617	3769581	286367	655	0	1	-2	0	0
6	0.2859	0.4042	0.2014	0.1085	857205	6429606	3768754	287205	655	0	1	-2	0	0
7	0.2852	0.4033	0.2033	0.1082	857205	6429606	3768666	287293	655	0	1	-2	1	0
8	0.2846	0.4023	0.2052	0.1079	857205	6429606	3768666	287293	655	0	1	-2	1	0
9	0.2839	0.4013	0.2071	0.1077	857205	6429593	3767282	288690	655	0	1	-2	1	0
10	0.2832	0.4004	0.2090	0.1074	857205	6413795	3781776	289994	655	0	1	-1	1	0
11	0.2825	0.3994	0.2109	0.1072	857205	6413795	3781776	289994	655	0	1	-1	1	0
12	0.2818	0.3985	0.2128	0.1069	857205	6424255	3785936	275374	655	0	1	-1	-4	0
13	0.2812	0.3975	0.2147	0.1066	857205	6424255	3785936	275374	655	0	1	-1	-4	0
14	0.2805	0.3965	0.2166	0.1064	857205	6424276	3787332	273957	655	0	1	-1	-4	0
15	0.2798	0.3956	0.2185	0.1061	857205	6424344	3787264	273957	655	0	1	-1	-4	0
16	0.2791	0.3946	0.2204	0.1059	857205	6421836	3786157	277572	655	0	1	-1	-3	0
17	0.2784	0.3937	0.2223	0.1056	857205	6421836	3786157	277572	655	0	1	-1	-3	0
18	0.2778	0.3927	0.2242	0.1054	857205	6419122	3783527	282916	655	0	1	-1	-1	0
19	0.2771	0.3917	0.2261	0.1051	857205	6419122	3783511	282932	655	0	1	-1	-1	0
20	0.2764	0.3908	0.2280	0.1048	857205	6419122	3770961	294827	1310	0	1	-2	3	100

Table 52. Summary table showing changes in cell cost values when the weight of criterion C10 – "Maximise distance to ground waters" is changed

%	Criterion weight values				Total number of cells in every cost class					Percentage change (%)				
PC	**C7**	**C8**	**C9**	**C10**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
-20	0.2972	0.4201	0.1947	0.0880	857205	6462244	3770620	252707	649	0	1	-2	-12	-1
-19	0.2968	0.4196	0.1945	0.0891	857205	6462244	3770620	252707	649	0	1	-2	-12	-1
-18	0.2965	0.4191	0.1942	0.0902	857205	6462244	3770620	252707	649	0	1	-2	-12	-1
-17	0.2961	0.4186	0.1940	0.0913	857205	6462244	3770620	252707	649	0	1	-2	-12	-1
-16	0.2957	0.4181	0.1938	0.0924	857205	6463550	3768442	253573	655	0	1	-2	-11	0
-15	0.2954	0.4176	0.1935	0.0935	857205	6463550	3768442	253573	655	0	1	-2	-11	0
-14	0.2950	0.4171	0.1933	0.0946	857205	6463550	3768442	253573	655	0	1	-2	-11	0
-13	0.2947	0.4166	0.1931	0.0957	857205	6463550	3768442	253573	655	0	1	-2	-11	0
-12	0.2943	0.4161	0.1928	0.0968	857205	6463550	3767128	254887	655	0	1	-2	-11	0
-11	0.2939	0.4156	0.1926	0.0979	857205	6463550	3767128	254887	655	0	1	-2	-11	0
-10	0.2936	0.4151	0.1923	0.0990	857205	6431872	3798781	254912	655	0	1	-1	-11	0
-9	0.2932	0.4146	0.1921	0.1001	857205	6431872	3798781	254912	655	0	1	-1	-11	0
-8	0.2929	0.4141	0.1919	0.1012	857205	6430709	3770486	284370	655	0	1	-2	-1	0
-7	0.2925	0.4135	0.1916	0.1023	857205	6430709	3770486	284370	655	0	1	-2	-1	0
-6	0.2922	0.4130	0.1914	0.1034	857205	6430709	3770486	284370	655	0	1	-2	-1	0
-5	0.2918	0.4125	0.1912	0.1045	857205	6424791	3776404	284370	655	0	1	-1	-1	0
-4	0.2914	0.4120	0.1909	0.1056	857205	6424791	3775345	285429	655	0	1	-1	0	0
-3	0.2911	0.4115	0.1907	0.1067	857205	6424791	3775345	285429	655	0	1	-1	0	0
-2	0.2907	0.4110	0.1905	0.1078	857205	6368818	3830886	285861	655	0	0	0	0	0
-1	0.2904	0.4105	0.1902	0.1089	857205	6368818	3830886	285861	655	0	0	0	0	0
0	**0.2900**	**0.4100**	**0.1900**	**0.1100**	**857205**	**6368818**	**3830886**	**285861**	**655**	**-**	**-**	**-**	**-**	**-**
1	0.2896	0.4095	0.1898	0.1111	857205	6368818	3830884	285863	655	0	0	0	0	0
2	0.2893	0.4090	0.1895	0.1122	857205	6368818	3830884	285863	655	0	0	0	0	0
3	0.2889	0.4085	0.1893	0.1133	857205	6368818	3830884	285863	655	0	0	0	0	0
4	0.2886	0.4080	0.1891	0.1144	857205	6368818	3830884	285863	655	0	0	0	0	0
5	0.2882	0.4075	0.1888	0.1155	857205	6368818	3830884	285863	655	0	0	0	0	0
6	0.2878	0.4070	0.1886	0.1166	857205	6368818	3830884	285863	655	0	0	0	0	0
7	0.2875	0.4065	0.1884	0.1177	857205	6368818	3830884	285863	655	0	0	0	0	0
8	0.2871	0.4059	0.1881	0.1188	857205	6368818	3830884	285863	655	0	0	0	0	0
9	0.2868	0.4054	0.1879	0.1199	857205	6363432	3822528	299457	803	0	0	0	5	23
10	0.2864	0.4049	0.1877	0.1210	857205	6363432	3822528	299457	803	0	0	0	5	23
11	0.2861	0.4044	0.1874	0.1221	857205	6363432	3822528	299457	803	0	0	0	5	23
12	0.2857	0.4039	0.1872	0.1232	857205	6363432	3822528	299457	803	0	0	0	5	23
13	0.2853	0.4034	0.1869	0.1243	857205	6363432	3822528	299457	803	0	0	0	5	23
14	0.2850	0.4029	0.1867	0.1254	857205	6363432	3822528	299457	803	0	0	0	5	23
15	0.2846	0.4024	0.1865	0.1265	857205	6363432	3822528	299457	803	0	0	0	5	23
16	0.2843	0.4019	0.1862	0.1276	857205	6363082	3821898	300437	803	0	0	0	5	23
17	0.2839	0.4014	0.1860	0.1287	857205	6363082	3821898	300437	803	0	0	0	5	23
18	0.2835	0.4009	0.1858	0.1298	857205	6363082	3821898	300437	803	0	0	0	5	23
19	0.2832	0.4004	0.1855	0.1309	857205	6363082	3821898	300437	803	0	0	0	5	23
20	0.2828	0.3999	0.1853	0.1320	857205	6363082	3821898	300437	803	0	0	0	5	23

Table 53. Summary table showing changes in cell cost values when the weight of criterion C11 – "Prioritise arable, grazing, forest and built-up land" is changed

%	Criterion weight values			Total number of cells in every cost class					Percentage change (%)				
PC	**C11**	**C12**	**C13**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
-20	0.5680	0.1639	0.2681	144535	3918053	6564890	715849	98	0	4	0	-18	-88
-19	0.5751	0.1612	0.2637	144535	3918053	6564890	715849	98	0	4	0	-18	-88
-18	0.5822	0.1585	0.2593	144535	3918053	6564890	715849	98	0	4	0	-18	-88
-17	0.5893	0.1558	0.2549	144535	3918053	6564890	715849	98	0	4	0	-18	-88
-16	0.5964	0.1531	0.2505	144535	3917186	6550505	730761	438	0	4	0	-17	-46
-15	0.6035	0.1504	0.2461	144535	3917186	6550505	730761	438	0	4	0	-17	-46
-14	0.6106	0.1477	0.2417	144535	3917186	6550505	730761	438	0	4	0	-17	-46
-13	0.6177	0.1450	0.2373	144535	3917186	6550505	730761	438	0	4	0	-17	-46
-12	0.6248	0.1423	0.2329	144535	3932373	6539063	727016	438	0	5	0	-17	-46
-11	0.6319	0.1396	0.2285	144535	3932373	6539063	727016	438	0	5	0	-17	-46
-10	0.6390	0.1369	0.2241	144535	3932373	6539063	727016	438	0	5	0	-17	-46
-9	0.6461	0.1342	0.2197	144535	3932373	6539063	727016	438	0	5	0	-17	-46
-8	0.6532	0.1315	0.2153	144535	3932373	6530219	735484	814	0	5	-1	-16	0
-7	0.6603	0.1289	0.2108	144535	3932373	6530219	735484	814	0	5	-1	-16	0
-6	0.6674	0.1262	0.2064	144535	3932373	6530219	735484	814	0	5	-1	-16	0
-5	0.6745	0.1235	0.2020	144535	3932373	6530219	735484	814	0	5	-1	-16	0
-4	0.6816	0.1208	0.1976	144535	3746110	6573804	878162	814	0	0	0	0	0
-3	0.6887	0.1181	0.1932	144535	3746110	6573804	878162	814	0	0	0	0	0
-2	0.6958	0.1154	0.1888	144535	3746110	6573804	878162	814	0	0	0	0	0
-1	0.7029	0.1127	0.1844	144535	3749419	6570507	878150	814	0	0	0	0	0
0	**0.7100**	**0.1100**	**0.1800**	**144535**	**3749419**	**6570507**	**878150**	**814**	**0**	**0**	**0**	**0**	**0**
1	0.7171	0.1073	0.1756	144535	3749419	6531105	917263	1103	0	0	-1	4	36
2	0.7242	0.1046	0.1712	144535	3749419	6531105	917263	1103	0	0	-1	4	36
3	0.7313	0.1019	0.1668	144535	3749419	6531105	917263	1103	0	0	-1	4	36
4	0.7384	0.0992	0.1624	144535	3751025	6529507	917255	1103	0	0	-1	4	36
5	0.7455	0.0965	0.1580	144535	3751025	6529507	917255	1103	0	0	-1	4	36
6	0.7526	0.0938	0.1536	144535	3751025	6529507	917255	1103	0	0	-1	4	36
7	0.7597	0.0911	0.1492	144535	3751025	6529507	917255	1103	0	0	-1	4	36
8	0.7668	0.0885	0.1447	144535	3759805	4409190	3020969	8926	0	0	-33	244	997
9	0.7739	0.0858	0.1403	144535	3759805	4409190	3020969	8926	0	0	-33	244	997
10	0.7810	0.0831	0.1359	144535	3759805	4409190	3020969	8926	0	0	-33	244	997
11	0.7881	0.0804	0.1315	144535	3759805	4409190	3020969	8926	0	0	-33	244	997
12	0.7952	0.0777	0.1271	144535	3759805	4409190	3020969	8926	0	0	-33	244	997
13	0.8023	0.0750	0.1227	144535	3759805	4409190	3020969	8926	0	0	-33	244	997
14	0.8094	0.0723	0.1183	144535	3759805	4409190	3020969	8926	0	0	-33	244	997
15	0.8165	0.0696	0.1139	144535	3759805	4409190	3020969	8926	0	0	-33	244	997
16	0.8236	0.0669	0.1095	144535	3759805	4409190	3020969	8926	0	0	-33	244	997
17	0.8307	0.0642	0.1051	144535	3759805	4409190	3020969	8926	0	0	-33	244	997
18	0.8378	0.0615	0.1007	144535	3759805	4409190	3020969	8926	0	0	-33	244	997
19	0.8449	0.0588	0.0963	144535	3759805	4409190	3020969	8926	0	0	-33	244	997
20	0.8520	0.0561	0.0919	144535	3759805	4409190	3020969	8926	0	0	-33	244	997

Table 54. Summary table showing changes in cell cost values when the weight of criterion C12 – "Maximise distance to residential areas to reduce air pollution" is changed

%	Criterion weight values			Total number of cells in every cost class					Percentage change (%)				
PC	**C11**	**C12**	**C13**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
-20	0.7276	0.0880	0.1844	144535	3751025	6529507	917255	1103	0	0	-1	4	36
-19	0.7267	0.0891	0.1842	144535	3751025	6529507	917255	1103	0	0	-1	4	36
-18	0.7258	0.0902	0.1840	144535	3751025	6529507	917255	1103	0	0	-1	4	36
-17	0.7249	0.0913	0.1838	144535	3751025	6529507	917255	1103	0	0	-1	4	36
-16	0.7240	0.0924	0.1836	144535	3751025	6529507	917255	1103	0	0	-1	4	36
-15	0.7232	0.0935	0.1833	144535	3751025	6529507	917255	1103	0	0	-1	4	36
-14	0.7223	0.0946	0.1831	144535	3751025	6529507	917255	1103	0	0	-1	4	36
-13	0.7214	0.0957	0.1829	144535	3751025	6529507	917255	1103	0	0	-1	4	36
-12	0.7205	0.0968	0.1827	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-11	0.7197	0.0979	0.1824	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-10	0.7188	0.0990	0.1822	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-9	0.7179	0.1001	0.1820	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-8	0.7170	0.1012	0.1818	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-7	0.7161	0.1023	0.1816	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-6	0.7153	0.1034	0.1813	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-5	0.7144	0.1045	0.1811	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-4	0.7135	0.1056	0.1809	144535	3749419	6570507	878150	814	0	0	0	0	0
-3	0.7126	0.1067	0.1807	144535	3749419	6570507	878150	814	0	0	0	0	0
-2	0.7118	0.1078	0.1804	144535	3749419	6570507	878150	814	0	0	0	0	0
-1	0.7109	0.1089	0.1802	144535	3749419	6570507	878150	814	0	0	0	0	0
0	**0.7100**	**0.1100**	**0.1800**	**144535**	**3749419**	**6570507**	**878150**	**814**	**0**	**0**	**0**	**0**	**0**
1	0.7091	0.1111	0.1798	144535	3749419	6570507	878150	814	0	0	0	0	0
2	0.7082	0.1122	0.1796	144535	3749419	6570507	878150	814	0	0	0	0	0
3	0.7074	0.1133	0.1793	144535	3749419	6570507	878150	814	0	0	0	0	0
4	0.7065	0.1144	0.1791	144535	3749419	6570507	878150	814	0	0	0	0	0
5	0.7056	0.1155	0.1789	144535	3749419	6570507	878150	814	0	0	0	0	0
6	0.7047	0.1166	0.1787	144535	3746110	6573804	878162	814	0	0	0	0	0
7	0.7039	0.1177	0.1784	144535	3746110	6573804	878162	814	0	0	0	0	0
8	0.7030	0.1188	0.1782	144535	3746110	6573804	878162	814	0	0	0	0	0
9	0.7021	0.1199	0.1780	144535	3746110	6573804	878162	814	0	0	0	0	0
10	0.7012	0.1210	0.1778	144535	3746110	6573804	878162	814	0	0	0	0	0
11	0.7003	0.1221	0.1776	144535	3746110	6573804	878162	814	0	0	0	0	0
12	0.6995	0.1232	0.1773	144535	3746110	6573804	878162	814	0	0	0	0	0
13	0.6986	0.1243	0.1771	144535	3746110	6573804	878162	814	0	0	0	0	0
14	0.6977	0.1254	0.1769	144535	3746110	6573804	878162	814	0	0	0	0	0
15	0.6968	0.1265	0.1767	144535	3746110	6573804	878162	814	0	0	0	0	0
16	0.6960	0.1276	0.1764	144535	3746110	6573804	878162	814	0	0	0	0	0
17	0.6951	0.1287	0.1762	144535	3746110	6573804	878162	814	0	0	0	0	0
18	0.6942	0.1298	0.1760	144535	3746110	6573804	878162	814	0	0	0	0	0
19	0.6933	0.1309	0.1758	144535	3746110	6573804	878162	814	0	0	0	0	0
20	0.6924	0.1320	0.1756	144535	3746110	6573804	878162	814	0	0	0	0	0

Table 55. Summary table showing changes in cell cost values when the weight of criterion C13 – "Maximise distance to residential areas to reduce noise pollution" is changed

%	Criterion weight values			Total number of cells in every cost class					Percentage change (%)				
PC	**C11**	**C12**	**C13**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
-20	0.7412	0.1148	0.1440	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-19	0.7396	0.1146	0.1458	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-18	0.7381	0.1143	0.1476	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-17	0.7365	0.1141	0.1494	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-16	0.7349	0.1139	0.1512	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-15	0.7334	0.1136	0.1530	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-14	0.7318	0.1134	0.1548	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-13	0.7303	0.1131	0.1566	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-12	0.7287	0.1129	0.1584	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-11	0.7271	0.1127	0.1602	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-10	0.7256	0.1124	0.1620	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-9	0.7240	0.1122	0.1638	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-8	0.7225	0.1119	0.1656	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-7	0.7209	0.1117	0.1674	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-6	0.7194	0.1114	0.1692	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-5	0.7178	0.1112	0.1710	144535	3749419	6531105	917263	1103	0	0	-1	4	36
-4	0.7162	0.1110	0.1728	144535	3749419	6570507	878150	814	0	0	0	0	0
-3	0.7147	0.1107	0.1746	144535	3749419	6570507	878150	814	0	0	0	0	0
-2	0.7131	0.1105	0.1764	144535	3749419	6570507	878150	814	0	0	0	0	0
-1	0.7116	0.1102	0.1782	144535	3749419	6570507	878150	814	0	0	0	0	0
0	**0.7100**	**0.1100**	**0.1800**	**144535**	**3749419**	**6570507**	**878150**	**814**	**0**	**0**	**0**	**0**	**0**
1	0.7084	0.1098	0.1818	144535	3749419	6570507	878150	814	0	0	0	0	0
2	0.7069	0.1095	0.1836	144535	3749419	6570507	878150	814	0	0	0	0	0
3	0.7053	0.1093	0.1854	144535	3749419	6570507	878150	814	0	0	0	0	0
4	0.7038	0.1090	0.1872	144535	3749419	6570507	878150	814	0	0	0	0	0
5	0.7022	0.1088	0.1890	144535	3749419	6570507	878150	814	0	0	0	0	0
6	0.7006	0.1086	0.1908	144535	3749419	6570507	878150	814	0	0	0	0	0
7	0.6991	0.1083	0.1926	144535	3749419	6570507	878150	814	0	0	0	0	0
8	0.6975	0.1081	0.1944	144535	3749419	6570507	878150	814	0	0	0	0	0
9	0.6960	0.1078	0.1962	144535	3749419	6570507	878150	814	0	0	0	0	0
10	0.6944	0.1076	0.1980	144535	3749419	6570507	878150	814	0	0	0	0	0
11	0.6929	0.1073	0.1998	144535	3749419	6570507	878150	814	0	0	0	0	0
12	0.6913	0.1071	0.2016	144535	3749419	6570507	878150	814	0	0	0	0	0
13	0.6897	0.1069	0.2034	144535	3749419	6570507	878150	814	0	0	0	0	0
14	0.6882	0.1066	0.2052	144535	3749419	6570507	878150	814	0	0	0	0	0
15	0.6866	0.1064	0.2070	144535	3749419	6570507	878150	814	0	0	0	0	0
16	0.6851	0.1061	0.2088	144535	3749419	6570507	878150	814	0	0	0	0	0
17	0.6835	0.1059	0.2106	144535	3749419	6570507	878150	814	0	0	0	0	0
18	0.6819	0.1057	0.2124	144535	3749419	6570507	878150	814	0	0	0	0	0
19	0.6804	0.1054	0.2142	144535	3749419	6570507	878150	814	0	0	0	0	0
20	0.6788	0.1052	0.2160	144535	3749419	6570507	878150	814	0	0	0	0	0

Table 56. Cell cost changes in raster dataset when the weight of criterion C1 – "Minimise unfavorable topographic conditions – slope of the terrain" changes

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
-20	774151	0	0	0	0	0	6069386	70479	0	0	0	12210	4123044	8917	0	0	0	98704	186534	0	0	0	0	0	0	190310
-19	774151	0	0	0	0	0	6069386	70479	0	0	0	12198	4123056	8917	0	0	0	98603	186635	0	0	0	0	0	0	190197
-18	774151	0	0	0	0	0	6077952	61913	0	0	0	11567	4123742	8862	0	0	0	98517	186721	0	0	0	0	0	0	180859
-17	774151	0	0	0	0	0	6077952	61913	0	0	0	11567	4123871	8733	0	0	0	98517	186721	0	0	0	0	0	0	180730
-16	774151	0	0	0	0	0	6077952	61913	0	0	0	11567	4123871	8733	0	0	0	98517	186721	0	0	0	0	0	0	180730
-15	774151	0	0	0	0	0	6079669	60196	0	0	0	10176	4125262	8733	0	0	0	98489	186749	0	0	0	0	0	0	177594
-14	774151	0	0	0	0	0	6079669	60196	0	0	0	8695	4126743	8733	0	0	0	89095	196143	0	0	0	0	0	0	166719
-13	774151	0	0	0	0	0	6079669	60196	0	0	0	8446	4126992	8733	0	0	0	89095	196143	0	0	0	0	0	0	166470
-12	774151	0	0	0	0	0	6110719	29146	0	0	0	8446	4128138	7587	0	0	0	89022	196216	0	0	0	0	0	0	134201
-11	774151	0	0	0	0	0	6110719	29146	0	0	0	8446	4128138	7587	0	0	0	89022	196216	0	0	0	0	0	0	134201
-10	774151	0	0	0	0	0	6122986	16879	0	0	0	8356	4128228	7587	0	0	0	89022	196216	0	0	0	0	0	0	121844
-9	774151	0	0	0	0	0	6122986	16879	0	0	0	8356	4128228	7587	0	0	0	89022	196216	0	0	0	0	0	0	121844
-8	774151	0	0	0	0	0	6122986	16879	0	0	0	8356	4128228	7587	0	0	0	89022	196216	0	0	0	0	0	0	121844
-7	774151	0	0	0	0	0	6137763	2102	0	0	0	74	4143993	104	0	0	0	16	285222	0	0	0	0	0	0	2296
-6	774151	0	0	0	0	0	6137763	2102	0	0	0	74	4143993	104	0	0	0	16	285222	0	0	0	0	0	0	2296
-5	774151	0	0	0	0	0	6137756	2109	0	0	0	74	4143993	104	0	0	0	16	285222	0	0	0	0	0	0	2303
-4	774151	0	0	0	0	0	6138001	1864	0	0	0	72	4144099	0	0	0	0	15	285223	0	0	0	0	0	0	1951
-3	774151	0	0	0	0	0	6137994	1871	0	0	0	67	4144104	0	0	0	0	15	285223	0	0	0	0	0	0	1953
-2	774151	0	0	0	0	0	6139865	0	0	0	0	67	4144104	0	0	0	0	3	285235	0	0	0	0	0	0	70
-1	774151	0	0	0	0	0	6139865	0	0	0	0	67	4144104	0	0	0	0	3	285235	0	0	0	0	0	0	70
0	**774151**	**0**	**0**	**0**	**0**	**0**	**6139865**	**0**	**0**	**0**	**0**	**0**	**4144171**	**0**	**0**	**0**	**0**	**0**	**285238**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
1	774151	0	0	0	0	0	6139668	197	0	0	0	0	4144111	60	0	0	0	0	285238	0	0	0	0	0	0	257
2	774151	0	0	0	0	0	6139668	197	0	0	0	0	4144111	60	0	0	0	0	285238	0	0	0	0	0	0	257
3	774151	0	0	0	0	0	6139668	197	0	0	0	654	4143457	60	0	0	0	118	285120	0	0	0	0	0	0	1029
4	774151	0	0	0	0	0	6139668	197	0	0	0	654	4143451	66	0	0	0	4040	281198	0	0	0	0	0	0	4957
5	774151	0	0	0	0	0	6133807	6058	0	0	0	1713	4125387	17071	0	0	0	4040	281198	0	0	0	0	0	0	28882
6	774151	0	0	0	0	0	6133807	6058	0	0	0	1713	4125387	17071	0	0	0	4040	281198	0	0	0	0	0	0	28882
7	774151	0	0	0	0	0	6133807	6058	0	0	0	1713	4125387	17071	0	0	0	4040	281198	0	0	0	0	0	0	28882
8	774151	0	0	0	0	0	6133742	6123	0	0	0	1763	4125336	17072	0	0	0	4362	280876	0	0	0	0	0	0	29320
9	774151	0	0	0	0	0	6133742	6123	0	0	0	1763	4125336	17072	0	0	0	4362	280876	0	0	0	0	0	0	29320
10	774151	0	0	0	0	0	6133742	6123	0	0	0	5865	4120895	17411	0	0	0	4497	280741	0	0	0	0	0	0	33896
11	774151	0	0	0	0	0	6133742	6123	0	0	0	5865	4120895	17411	0	0	0	4497	280741	0	0	0	0	0	0	33896
12	774151	0	0	0	0	0	6133683	6182	0	0	0	5865	4117495	20811	0	0	0	4497	280741	0	0	0	0	0	0	37355
13	774151	0	0	0	0	0	6133683	6182	0	0	0	5865	4117495	20811	0	0	0	4497	280741	0	0	0	0	0	0	37355
14	774151	0	0	0	0	0	6133683	6182	0	0	0	9002	4114336	20833	0	0	0	4728	280510	0	0	0	0	0	0	40745
15	774151	0	0	0	0	0	6133341	6524	0	0	0	9002	4114335	20834	0	0	0	4728	280510	0	0	0	0	0	0	41088
16	774151	0	0	0	0	0	6133341	6524	0	0	0	9002	4114335	20834	0	0	0	4728	280510	0	0	0	0	0	0	41088
17	774151	0	0	0	0	0	6133258	6607	0	0	0	9003	4113779	21389	0	0	0	4728	280510	0	0	0	0	0	0	41727
18	774151	0	0	0	0	0	6126359	13506	0	0	0	13241	4106892	24038	0	0	0	8069	277169	0	0	0	0	0	0	58854
19	774151	0	0	0	0	0	6126359	13506	0	0	0	13241	4106892	24038	0	0	0	8069	277169	0	0	0	0	0	0	58854
20	774151	0	0	0	0	0	6126352	13513	0	0	0	13241	4106892	24038	0	0	0	8069	277169	0	0	0	0	0	0	58861

Table 57. Cell cost changes in raster dataset when the weight of criterion C2 – "Minimise a number of by-pass crossings with roads with high priority" changes

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
-20	774151	0	0	0	0	0	6129322	10543	0	0	0	47	4125589	18535	0	0	0	110	285006	122	0	0	0	0	0	29357
-19	774151	0	0	0	0	0	6129322	10543	0	0	0	47	4125589	18535	0	0	0	110	285006	122	0	0	0	0	0	29357
-18	774151	0	0	0	0	0	6129322	10543	0	0	0	47	4125589	18535	0	0	0	110	285006	122	0	0	0	0	0	29357
-17	774151	0	0	0	0	0	6129322	10543	0	0	0	47	4125589	18535	0	0	0	110	285006	122	0	0	0	0	0	29357
-16	774151	0	0	0	0	0	6130300	9565	0	0	0	42	4126062	18067	0	0	0	110	285006	122	0	0	0	0	0	27906
-15	774151	0	0	0	0	0	6130300	9565	0	0	0	42	4126062	18067	0	0	0	110	285006	122	0	0	0	0	0	27906
-14	774151	0	0	0	0	0	6130300	9565	0	0	0	42	4126062	18067	0	0	0	110	285006	122	0	0	0	0	0	27906
-13	774151	0	0	0	0	0	6130300	9565	0	0	0	42	4126062	18067	0	0	0	110	285006	122	0	0	0	0	0	27906
-12	774151	0	0	0	0	0	6130300	9565	0	0	0	42	4126068	18061	0	0	0	110	285006	122	0	0	0	0	0	27900
-11	774151	0	0	0	0	0	6130300	9565	0	0	0	42	4126068	18061	0	0	0	110	285006	122	0	0	0	0	0	27900
-10	774151	0	0	0	0	0	6130300	9565	0	0	0	27	4126083	18061	0	0	0	71	285045	122	0	0	0	0	0	27846
-9	774151	0	0	0	0	0	6130300	9565	0	0	0	27	4126083	18061	0	0	0	71	285045	122	0	0	0	0	0	27846
-8	774151	0	0	0	0	0	6139661	204	0	0	0	27	4144084	60	0	0	0	59	285179	0	0	0	0	0	0	350
-7	774151	0	0	0	0	0	6139661	204	0	0	0	27	4144084	60	0	0	0	59	285179	0	0	0	0	0	0	350
-6	774151	0	0	0	0	0	6139661	204	0	0	0	27	4144084	60	0	0	0	59	285179	0	0	0	0	0	0	350
-5	774151	0	0	0	0	0	6139661	204	0	0	0	27	4144084	60	0	0	0	59	285179	0	0	0	0	0	0	350
-4	774151	0	0	0	0	0	6139661	204	0	0	0	27	4144084	60	0	0	0	59	285179	0	0	0	0	0	0	350
-3	774151	0	0	0	0	0	6139661	204	0	0	0	27	4144084	60	0	0	0	59	285179	0	0	0	0	0	0	350
-2	774151	0	0	0	0	0	6139661	204	0	0	0	0	4144111	60	0	0	0	0	285238	0	0	0	0	0	0	264
-1	774151	0	0	0	0	0	6139661	204	0	0	0	0	4144111	60	0	0	0	0	285238	0	0	0	0	0	0	264
0	**774151**	**0**	**0**	**0**	**0**	**0**	**6139865**	**0**	**0**	**0**	**0**	**0**	**4144171**	**0**	**0**	**0**	**0**	**0**	**285238**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
1	774151	0	0	0	0	0	6139849	16	0	0	0	0	4144171	0	0	0	0	0	285238	0	0	0	0	0	0	16
2	774151	0	0	0	0	0	6139849	16	0	0	0	0	4144171	0	0	0	0	0	285238	0	0	0	0	0	0	16
3	774151	0	0	0	0	0	6139849	16	0	0	0	0	4144171	0	0	0	0	0	285238	0	0	0	0	0	0	16
4	774151	0	0	0	0	0	6139849	16	0	0	0	0	4144171	0	0	0	0	0	285238	0	0	0	0	0	0	16
5	774151	0	0	0	0	0	6139849	16	0	0	0	282	4143889	0	0	0	0	422	284816	0	0	0	0	0	0	720
6	774151	0	0	0	0	0	6139849	16	0	0	0	282	4143889	0	0	0	0	422	284816	0	0	0	0	0	0	720
7	774151	0	0	0	0	0	6139849	16	0	0	0	282	4143889	0	0	0	0	422	284816	0	0	0	0	0	0	720
8	774151	0	0	0	0	0	6139849	16	0	0	0	282	4143889	0	0	0	0	422	284816	0	0	0	0	0	0	720
9	774151	0	0	0	0	0	6139849	16	0	0	0	964	4143205	2	0	0	0	540	284698	0	0	0	0	0	0	1522
10	774151	0	0	0	0	0	6139849	16	0	0	0	964	4143205	2	0	0	0	540	284698	0	0	0	0	0	0	1522
11	774151	0	0	0	0	0	6139849	16	0	0	0	964	4143205	2	0	0	0	540	284698	0	0	0	0	0	0	1522
12	774151	0	0	0	0	0	6139845	20	0	0	0	964	4143205	2	0	0	0	4465	280773	0	0	0	0	0	0	5451
13	774151	0	0	0	0	0	6139845	20	0	0	0	964	4143205	2	0	0	0	4465	280773	0	0	0	0	0	0	5451
14	774151	0	0	0	0	0	6139845	20	0	0	0	964	4143205	2	0	0	0	4465	280773	0	0	0	0	0	0	5451
15	774151	0	0	0	0	0	6139845	20	0	0	0	964	4143205	2	0	0	0	4465	280773	0	0	0	0	0	0	5451
16	774151	0	0	0	0	0	6139157	708	0	0	0	2031	4142005	135	0	0	0	4562	280676	0	0	0	0	0	0	7436
17	774151	0	0	0	0	0	6139157	708	0	0	0	2031	4142005	135	0	0	0	4562	280676	0	0	0	0	0	0	7436
18	774151	0	0	0	0	0	6139157	708	0	0	0	2031	4142005	135	0	0	0	4562	280676	0	0	0	0	0	0	7436
19	774151	0	0	0	0	0	6139157	708	0	0	0	2031	4142005	135	0	0	0	4562	280676	0	0	0	0	0	0	7436
20	774151	0	0	0	0	0	6139157	708	0	0	0	2031	4141827	313	0	0	0	4562	280676	0	0	0	0	0	0	7614

Table 58. Cell cost changes in raster dataset when the weight of criterion C3 – "Minimise a number of by-pass crossings with rivers with high-order drainage" changes

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
-20	774151	0	0	0	0	0	6116897	22968	0	0	0	2291	4117314	24566	0	0	0	4723	280515	0	0	0	0	0	0	54548
-19	774151	0	0	0	0	0	6116909	22956	0	0	0	2290	4117372	24509	0	0	0	4723	280515	0	0	0	0	0	0	54478
-18	774151	0	0	0	0	0	6116909	22956	0	0	0	2290	4117372	24509	0	0	0	4723	280515	0	0	0	0	0	0	54478
-17	774151	0	0	0	0	0	6116909	22956	0	0	0	2290	4117372	24509	0	0	0	4723	280515	0	0	0	0	0	0	54478
-16	774151	0	0	0	0	0	6131027	8838	0	0	0	2269	4124634	17268	0	0	0	4714	280524	0	0	0	0	0	0	33089
-15	774151	0	0	0	0	0	6131027	8838	0	0	0	2269	4124634	17268	0	0	0	4714	280524	0	0	0	0	0	0	33089
-14	774151	0	0	0	0	0	6131027	8838	0	0	0	1850	4125053	17268	0	0	0	4411	280827	0	0	0	0	0	0	32367
-13	774151	0	0	0	0	0	6131027	8838	0	0	0	1779	4125124	17268	0	0	0	4411	280827	0	0	0	0	0	0	32296
-12	774151	0	0	0	0	0	6131027	8838	0	0	0	1779	4125124	17268	0	0	0	4411	280827	0	0	0	0	0	0	32296
-11	774151	0	0	0	0	0	6131027	8838	0	0	0	1779	4125124	17268	0	0	0	4411	280827	0	0	0	0	0	0	32296
-10	774151	0	0	0	0	0	6132160	7705	0	0	0	695	4126497	16979	0	0	0	4403	280835	0	0	0	0	0	0	29782
-9	774151	0	0	0	0	0	6132160	7705	0	0	0	695	4126497	16979	0	0	0	4403	280835	0	0	0	0	0	0	29782
-8	774151	0	0	0	0	0	6132160	7705	0	0	0	695	4126497	16979	0	0	0	4403	280835	0	0	0	0	0	0	29782
-7	774151	0	0	0	0	0	6132160	7705	0	0	0	695	4126503	16973	0	0	0	481	284757	0	0	0	0	0	0	25854
-6	774151	0	0	0	0	0	6132160	7705	0	0	0	695	4126503	16973	0	0	0	481	284757	0	0	0	0	0	0	25854
-5	774151	0	0	0	0	0	6139652	213	0	0	0	504	4143639	28	0	0	0	111	285127	0	0	0	0	0	0	856
-4	774151	0	0	0	0	0	6139652	213	0	0	0	504	4143639	28	0	0	0	111	285127	0	0	0	0	0	0	856
-3	774151	0	0	0	0	0	6139652	213	0	0	0	504	4143639	28	0	0	0	111	285127	0	0	0	0	0	0	856
-2	774151	0	0	0	0	0	6139645	220	0	0	0	202	4143941	28	0	0	0	0	285238	0	0	0	0	0	0	450
-1	774151	0	0	0	0	0	6139652	213	0	0	0	0	4144143	28	0	0	0	0	285238	0	0	0	0	0	0	241
0	**774151**	**0**	**0**	**0**	**0**	**0**	**6139865**	**0**	**0**	**0**	**0**	**0**	**4144171**	**0**	**0**	**0**	**0**	**0**	**285238**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
1	774151	0	0	0	0	0	6139865	0	0	0	0	0	4144139	32	0	0	0	0	285238	0	0	0	0	0	0	32
2	774151	0	0	0	0	0	6139865	0	0	0	0	0	4144139	32	0	0	0	0	285238	0	0	0	0	0	0	32
3	774151	0	0	0	0	0	6138021	1844	0	0	0	0	4144139	32	0	0	0	0	285238	0	0	0	0	0	0	1876
4	774151	0	0	0	0	0	6138021	1844	0	0	0	0	4144139	32	0	0	0	0	285238	0	0	0	0	0	0	1876
5	774151	0	0	0	0	0	6138021	1844	0	0	0	0	4144139	32	0	0	0	0	285238	0	0	0	0	0	0	1876
6	774151	0	0	0	0	0	6138020	1845	0	0	0	252	4142905	1014	0	0	0	179	284937	122	0	0	0	0	0	3412
7	774151	0	0	0	0	0	6138020	1845	0	0	0	252	4142905	1014	0	0	0	179	284937	122	0	0	0	0	0	3412
8	774151	0	0	0	0	0	6137382	2483	0	0	0	252	4142662	1257	0	0	0	179	284937	122	0	0	0	0	0	4293
9	774151	0	0	0	0	0	6137382	2483	0	0	0	252	4142662	1257	0	0	0	179	284937	122	0	0	0	0	0	4293
10	774151	0	0	0	0	0	6137382	2483	0	0	0	252	4142662	1257	0	0	0	179	284937	122	0	0	0	0	0	4293
11	774151	0	0	0	0	0	6123911	15954	0	0	0	1118	4141796	1257	0	0	0	179	284937	122	0	0	0	0	0	18630
12	774151	0	0	0	0	0	6123911	15954	0	0	0	1118	4141796	1257	0	0	0	179	284937	122	0	0	0	0	0	18630
13	774151	0	0	0	0	0	6123911	15954	0	0	0	1118	4141618	1435	0	0	0	179	284937	122	0	0	0	0	0	18808
14	774151	0	0	0	0	0	6120698	19167	0	0	0	1118	4138992	4061	0	0	0	179	284937	122	0	0	0	0	0	24647
15	774151	0	0	0	0	0	6120698	19167	0	0	0	1118	4138992	4061	0	0	0	179	284937	122	0	0	0	0	0	24647
16	774151	0	0	0	0	0	6120698	19167	0	0	0	40389	4099721	4061	0	0	0	89470	195646	122	0	0	0	0	0	153209
17	774151	0	0	0	0	0	6120698	19167	0	0	0	40389	4099721	4061	0	0	0	89470	195646	122	0	0	0	0	0	153209
18	774151	0	0	0	0	0	6120698	19167	0	0	0	40389	4099719	4063	0	0	0	89470	195646	122	0	0	0	0	0	153211
19	774151	0	0	0	0	0	6120691	19174	0	0	0	40389	4099719	4063	0	0	0	89470	195646	122	0	0	0	0	0	153218
20	774151	0	0	0	0	0	6120698	19167	0	0	0	40389	4099719	4063	0	0	0	89470	195646	122	0	0	0	0	0	153211

Table 59. Cell cost changes in raster dataset when the weight of criterion C4 – "Maximise distance to flooding areas" changes

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
-20	774151	0	0	0	0	0	6133915	5950	0	0	0	988	4126177	17006	0	0	0	438	284800	0	0	0	0	0	0	24382
-19	774151	0	0	0	0	0	6133922	5943	0	0	0	988	4126177	17006	0	0	0	438	284800	0	0	0	0	0	0	24375
-18	774151	0	0	0	0	0	6133922	5943	0	0	0	988	4126177	17006	0	0	0	438	284800	0	0	0	0	0	0	24375
-17	774151	0	0	0	0	0	6133922	5943	0	0	0	973	4126192	17006	0	0	0	399	284839	0	0	0	0	0	0	24321
-16	774151	0	0	0	0	0	6133922	5943	0	0	0	973	4126192	17006	0	0	0	399	284839	0	0	0	0	0	0	24321
-15	774151	0	0	0	0	0	6133922	5943	0	0	0	973	4126192	17006	0	0	0	399	284839	0	0	0	0	0	0	24321
-14	774151	0	0	0	0	0	6133922	5943	0	0	0	973	4126192	17006	0	0	0	399	284839	0	0	0	0	0	0	24321
-13	774151	0	0	0	0	0	6139776	89	0	0	0	904	4143264	3	0	0	0	77	285161	0	0	0	0	0	0	1073
-12	774151	0	0	0	0	0	6139783	82	0	0	0	904	4143264	3	0	0	0	77	285161	0	0	0	0	0	0	1066
-11	774151	0	0	0	0	0	6139783	82	0	0	0	904	4143264	3	0	0	0	77	285161	0	0	0	0	0	0	1066
-10	774151	0	0	0	0	0	6139783	82	0	0	0	904	4143264	3	0	0	0	77	285161	0	0	0	0	0	0	1066
-9	774151	0	0	0	0	0	6139783	82	0	0	0	904	4143264	3	0	0	0	77	285161	0	0	0	0	0	0	1066
-8	774151	0	0	0	0	0	6139783	82	0	0	0	274	4143894	3	0	0	0	76	285162	0	0	0	0	0	0	435
-7	774151	0	0	0	0	0	6139783	82	0	0	0	274	4143894	3	0	0	0	76	285162	0	0	0	0	0	0	435
-6	774151	0	0	0	0	0	6139776	89	0	0	0	27	4144141	3	0	0	0	59	285179	0	0	0	0	0	0	178
-5	774151	0	0	0	0	0	6139783	82	0	0	0	27	4144141	3	0	0	0	59	285179	0	0	0	0	0	0	171
-4	774151	0	0	0	0	0	6139783	82	0	0	0	0	4144168	3	0	0	0	0	285238	0	0	0	0	0	0	85
-3	774151	0	0	0	0	0	6139783	82	0	0	0	0	4144168	3	0	0	0	0	285238	0	0	0	0	0	0	85
-2	774151	0	0	0	0	0	6139783	82	0	0	0	0	4144168	3	0	0	0	0	285238	0	0	0	0	0	0	85
-1	774151	0	0	0	0	0	6139783	82	0	0	0	0	4144168	3	0	0	0	0	285238	0	0	0	0	0	0	85
0	**774151**	**0**	**0**	**0**	**0**	**0**	**6139865**	**0**	**0**	**0**	**0**	**0**	**4144171**	**0**	**0**	**0**	**0**	**0**	**285238**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
1	774151	0	0	0	0	0	6139743	122	0	0	0	0	4144114	57	0	0	0	0	285238	0	0	0	0	0	0	179
2	774151	0	0	0	0	0	6139750	115	0	0	0	0	4144114	57	0	0	0	0	285238	0	0	0	0	0	0	172
3	774151	0	0	0	0	0	6139750	115	0	0	0	0	4144114	57	0	0	0	0	285238	0	0	0	0	0	0	172
4	774151	0	0	0	0	0	6139750	115	0	0	0	0	4144114	57	0	0	0	0	285238	0	0	0	0	0	0	172
5	774151	0	0	0	0	0	6138114	1751	0	0	0	0	4144098	73	0	0	0	0	285238	0	0	0	0	0	0	1824
6	774151	0	0	0	0	0	6138114	1751	0	0	0	0	4144098	73	0	0	0	0	285238	0	0	0	0	0	0	1824
7	774151	0	0	0	0	0	6138114	1751	0	0	0	282	4143816	73	0	0	0	422	284816	0	0	0	0	0	0	2528
8	774151	0	0	0	0	0	6138107	1758	0	0	0	282	4143816	73	0	0	0	422	284816	0	0	0	0	0	0	2535
9	774151	0	0	0	0	0	6137876	1989	0	0	0	282	4143712	177	0	0	0	422	284816	0	0	0	0	0	0	2870
10	774151	0	0	0	0	0	6137876	1989	0	0	0	282	4143712	177	0	0	0	422	284816	0	0	0	0	0	0	2870
11	774151	0	0	0	0	0	6137876	1989	0	0	0	282	4143712	177	0	0	0	422	284816	0	0	0	0	0	0	2870
12	774151	0	0	0	0	0	6137876	1989	0	0	0	282	4143712	177	0	0	0	422	284816	0	0	0	0	0	0	2870
13	774151	0	0	0	0	0	6137876	1989	0	0	0	282	4143712	177	0	0	0	422	284816	0	0	0	0	0	0	2870
14	774151	0	0	0	0	0	6122216	17649	0	0	0	689	4134843	8639	0	0	0	535	284581	122	0	0	0	0	0	27634
15	774151	0	0	0	0	0	6122209	17656	0	0	0	689	4134843	8639	0	0	0	535	284581	122	0	0	0	0	0	27641
16	774151	0	0	0	0	0	6122216	17649	0	0	0	689	4134843	8639	0	0	0	535	284581	122	0	0	0	0	0	27634
17	774151	0	0	0	0	0	6122216	17649	0	0	0	689	4134843	8639	0	0	0	535	284581	122	0	0	0	0	0	27634
18	774151	0	0	0	0	0	6122216	17649	0	0	0	689	4134843	8639	0	0	0	535	284581	122	0	0	0	0	0	27634
19	774151	0	0	0	0	0	6122216	17649	0	0	0	689	4134843	8639	0	0	0	535	284581	122	0	0	0	0	0	27634
20	774151	0	0	0	0	0	6122216	17649	0	0	0	689	4134843	8639	0	0	0	535	284581	122	0	0	0	0	0	27634

Table 60. Cell cost changes in raster dataset when the weight of criterion C5 – "Maximise geological construction suitability" changes

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
-20	774151	0	0	0	0	0	6127505	12360	0	0	0	38214	4104221	1736	0	0	0	4745	280371	122	0	0	0	0	0	57177
-19	774151	0	0	0	0	0	6127505	12360	0	0	0	38214	4104399	1558	0	0	0	4745	280371	122	0	0	0	0	0	56999
-18	774151	0	0	0	0	0	6127505	12360	0	0	0	38214	4104399	1558	0	0	0	4745	280371	122	0	0	0	0	0	56999
-17	774151	0	0	0	0	0	6127505	12360	0	0	0	36396	4106217	1558	0	0	0	4745	280371	122	0	0	0	0	0	55181
-16	774151	0	0	0	0	0	6127505	12360	0	0	0	36396	4106217	1558	0	0	0	4745	280371	122	0	0	0	0	0	55181
-15	774151	0	0	0	0	0	6139329	536	0	0	0	32299	4110664	1208	0	0	0	4646	280470	122	0	0	0	0	0	38811
-14	774151	0	0	0	0	0	6139329	536	0	0	0	32299	4110664	1208	0	0	0	4646	280470	122	0	0	0	0	0	38811
-13	774151	0	0	0	0	0	6139329	536	0	0	0	32299	4110664	1208	0	0	0	4646	280470	122	0	0	0	0	0	38811
-12	774151	0	0	0	0	0	6139329	536	0	0	0	32299	4110664	1208	0	0	0	4646	280470	122	0	0	0	0	0	38811
-11	774151	0	0	0	0	0	6139333	532	0	0	0	1302	4141662	1207	0	0	0	419	284697	122	0	0	0	0	0	3582
-10	774151	0	0	0	0	0	6139333	532	0	0	0	1302	4141662	1207	0	0	0	419	284697	122	0	0	0	0	0	3582
-9	774151	0	0	0	0	0	6139333	532	0	0	0	1302	4141749	1120	0	0	0	419	284697	122	0	0	0	0	0	3495
-8	774151	0	0	0	0	0	6139333	532	0	0	0	1302	4141749	1120	0	0	0	419	284697	122	0	0	0	0	0	3495
-7	774151	0	0	0	0	0	6139858	7	0	0	0	674	4142483	1014	0	0	0	419	284697	122	0	0	0	0	0	2236
-6	774151	0	0	0	0	0	6139858	7	0	0	0	674	4142483	1014	0	0	0	419	284697	122	0	0	0	0	0	2236
-5	774151	0	0	0	0	0	6139858	7	0	0	0	674	4142483	1014	0	0	0	419	284697	122	0	0	0	0	0	2236
-4	774151	0	0	0	0	0	6139858	7	0	0	0	674	4142483	1014	0	0	0	419	284697	122	0	0	0	0	0	2236
-3	774151	0	0	0	0	0	6139858	7	0	0	0	0	4144139	32	0	0	0	0	285238	0	0	0	0	0	0	39
-2	774151	0	0	0	0	0	6139858	7	0	0	0	0	4144139	32	0	0	0	0	285238	0	0	0	0	0	0	39
-1	774151	0	0	0	0	0	6139858	7	0	0	0	0	4144139	32	0	0	0	0	285238	0	0	0	0	0	0	39
0	**774151**	**0**	**0**	**0**	**0**	**0**	**6139865**	**0**	**0**	**0**	**0**	**0**	**4144171**	**0**	**0**	**0**	**0**	**0**	**285238**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
1	774151	0	0	0	0	0	6139767	98	0	0	0	0	4144168	3	0	0	0	0	285238	0	0	0	0	0	0	101
2	774151	0	0	0	0	0	6139767	98	0	0	0	0	4144168	3	0	0	0	0	285238	0	0	0	0	0	0	101
3	774151	0	0	0	0	0	6139767	98	0	0	0	0	4144168	3	0	0	0	0	285238	0	0	0	0	0	0	101
4	774151	0	0	0	0	0	6138131	1734	0	0	0	341	4143811	19	0	0	0	79	285159	0	0	0	0	0	0	2173
5	774151	0	0	0	0	0	6138131	1734	0	0	0	341	4143811	19	0	0	0	79	285159	0	0	0	0	0	0	2173
6	774151	0	0	0	0	0	6138016	1849	0	0	0	341	4143786	44	0	0	0	79	285159	0	0	0	0	0	0	2313
7	774151	0	0	0	0	0	6138131	1734	0	0	0	341	4143811	19	0	0	0	79	285159	0	0	0	0	0	0	2173
8	774151	0	0	0	0	0	6131827	8038	0	0	0	343	4126806	17022	0	0	0	80	285158	0	0	0	0	0	0	25483
9	774151	0	0	0	0	0	6131827	8038	0	0	0	343	4126806	17022	0	0	0	80	285158	0	0	0	0	0	0	25483
10	774151	0	0	0	0	0	6102609	37256	0	0	0	343	4125838	17990	0	0	0	80	285158	0	0	0	0	0	0	55669
11	774151	0	0	0	0	0	6101345	38520	0	0	0	389	4125788	17994	0	0	0	404	284834	0	0	0	0	0	0	57307
12	774151	0	0	0	0	0	6101345	38520	0	0	0	389	4125788	17994	0	0	0	404	284834	0	0	0	0	0	0	57307
13	774151	0	0	0	0	0	6092785	47080	0	0	0	389	4125788	17994	0	0	0	404	284834	0	0	0	0	0	0	65867
14	774151	0	0	0	0	0	6092785	47080	0	0	0	389	4125788	17994	0	0	0	404	284834	0	0	0	0	0	0	65867
15	774151	0	0	0	0	0	6089968	49897	0	0	0	409	4125686	18076	0	0	0	443	284795	0	0	0	0	0	0	68825
16	774151	0	0	0	0	0	6089968	49897	0	0	0	409	4125686	18076	0	0	0	443	284795	0	0	0	0	0	0	68825
17	774151	0	0	0	0	0	6089968	49897	0	0	0	409	4125686	18076	0	0	0	443	284795	0	0	0	0	0	0	68825
18	774151	0	0	0	0	0	6088136	51729	0	0	0	1077	4125018	18076	0	0	0	2857	282381	0	0	0	0	0	0	73739
19	774151	0	0	0	0	0	6088136	51729	0	0	0	1077	4125018	18076	0	0	0	2857	282381	0	0	0	0	0	0	73739
20	774151	0	0	0	0	0	6088136	51729	0	0	0	1077	4125018	18076	0	0	0	2857	282381	0	0	0	0	0	0	73739

Table 61. Cell cost changes in raster dataset when the weight of criterion C6 – "Maximise soil construction suitability" changes

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
-20	774151	0	0	0	0	0	6137377	2488	0	0	0	36401	4107446	324	0	0	0	7297	277941	0	0	0	0	0	0	46510
-19	774151	0	0	0	0	0	6137377	2488	0	0	0	36400	4107449	322	0	0	0	7297	277941	0	0	0	0	0	0	46507
-18	774151	0	0	0	0	0	6137377	2488	0	0	0	36400	4107449	322	0	0	0	7297	277941	0	0	0	0	0	0	46507
-17	774151	0	0	0	0	0	6137377	2488	0	0	0	36400	4107449	322	0	0	0	7297	277941	0	0	0	0	0	0	46507
-16	774151	0	0	0	0	0	6138015	1850	0	0	0	3607	4140486	78	0	0	0	2970	282268	0	0	0	0	0	0	8505
-15	774151	0	0	0	0	0	6138015	1850	0	0	0	3607	4140486	78	0	0	0	2970	282268	0	0	0	0	0	0	8505
-14	774151	0	0	0	0	0	6138015	1850	0	0	0	3607	4140486	78	0	0	0	2970	282268	0	0	0	0	0	0	8505
-13	774151	0	0	0	0	0	6138015	1850	0	0	0	2754	4141339	78	0	0	0	595	284643	0	0	0	0	0	0	5277
-12	774151	0	0	0	0	0	6138015	1850	0	0	0	2754	4141339	78	0	0	0	595	284643	0	0	0	0	0	0	5277
-11	774151	0	0	0	0	0	6138015	1850	0	0	0	2754	4141339	78	0	0	0	595	284643	0	0	0	0	0	0	5277
-10	774151	0	0	0	0	0	6138016	1849	0	0	0	734	4143361	76	0	0	0	499	284739	0	0	0	0	0	0	3158
-9	774151	0	0	0	0	0	6138016	1849	0	0	0	734	4143361	76	0	0	0	499	284739	0	0	0	0	0	0	3158
-8	774151	0	0	0	0	0	6138016	1849	0	0	0	734	4143361	76	0	0	0	499	284739	0	0	0	0	0	0	3158
-7	774151	0	0	0	0	0	6138016	1849	0	0	0	734	4143361	76	0	0	0	496	284742	0	0	0	0	0	0	3155
-6	774151	0	0	0	0	0	6138016	1849	0	0	0	734	4143361	76	0	0	0	496	284742	0	0	0	0	0	0	3155
-5	774151	0	0	0	0	0	6139652	213	0	0	0	308	4143803	60	0	0	0	112	285126	0	0	0	0	0	0	693
-4	774151	0	0	0	0	0	6139652	213	0	0	0	308	4143803	60	0	0	0	112	285126	0	0	0	0	0	0	693
-3	774151	0	0	0	0	0	6139652	213	0	0	0	308	4143803	60	0	0	0	112	285126	0	0	0	0	0	0	693
-2	774151	0	0	0	0	0	6139652	213	0	0	0	0	4144111	60	0	0	0	0	285238	0	0	0	0	0	0	273
-1	774151	0	0	0	0	0	6139652	213	0	0	0	0	4144111	60	0	0	0	0	285238	0	0	0	0	0	0	273
0	**774151**	**0**	**0**	**0**	**0**	**0**	**6139865**	**0**	**0**	**0**	**0**	**0**	**4144171**	**0**	**0**	**0**	**0**	**0**	**285238**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
1	774151	0	0	0	0	0	6139858	7	0	0	0	0	4144171	0	0	0	0	0	285238	0	0	0	0	0	0	7
2	774151	0	0	0	0	0	6139858	7	0	0	0	0	4144171	0	0	0	0	0	285238	0	0	0	0	0	0	7
3	774151	0	0	0	0	0	6139838	27	0	0	0	0	4144171	0	0	0	0	0	285238	0	0	0	0	0	0	27
4	774151	0	0	0	0	0	6139838	27	0	0	0	0	4144171	0	0	0	0	0	285238	0	0	0	0	0	0	27
5	774151	0	0	0	0	0	6139838	27	0	0	0	0	4144171	0	0	0	0	0	285238	0	0	0	0	0	0	27
6	774151	0	0	0	0	0	6138710	1155	0	0	0	55	4143903	213	0	0	0	71	285167	0	0	0	0	0	0	1494
7	774151	0	0	0	0	0	6138710	1155	0	0	0	55	4143903	213	0	0	0	71	285167	0	0	0	0	0	0	1494
8	774151	0	0	0	0	0	6124588	15277	0	0	0	55	4136663	7453	0	0	0	71	285167	0	0	0	0	0	0	22856
9	774151	0	0	0	0	0	6124588	15277	0	0	0	55	4136663	7453	0	0	0	71	285167	0	0	0	0	0	0	22856
10	774151	0	0	0	0	0	6124588	15277	0	0	0	55	4136663	7453	0	0	0	71	285167	0	0	0	0	0	0	22856
11	774151	0	0	0	0	0	6106821	33044	0	0	0	250	4118543	25378	0	0	0	72	285044	122	0	0	0	0	0	58866
12	774151	0	0	0	0	0	6106821	33044	0	0	0	250	4118543	25378	0	0	0	72	285044	122	0	0	0	0	0	58866
13	774151	0	0	0	0	0	6106821	33044	0	0	0	250	4118543	25378	0	0	0	72	285044	122	0	0	0	0	0	58866
14	774151	0	0	0	0	0	6106821	33044	0	0	0	250	4118543	25378	0	0	0	72	285044	122	0	0	0	0	0	58866
15	774151	0	0	0	0	0	6106821	33044	0	0	0	250	4118543	25378	0	0	0	72	285044	122	0	0	0	0	0	58866
16	774151	0	0	0	0	0	6106734	33131	0	0	0	307	4118486	25378	0	0	0	397	284719	122	0	0	0	0	0	59335
17	774151	0	0	0	0	0	6106734	33131	0	0	0	307	4118486	25378	0	0	0	397	284719	122	0	0	0	0	0	59335
18	774151	0	0	0	0	0	6106655	33210	0	0	0	307	4118429	25435	0	0	0	397	284719	122	0	0	0	0	0	59471
19	774151	0	0	0	0	0	6106655	33210	0	0	0	307	4118429	25435	0	0	0	397	284719	122	0	0	0	0	0	59471
20	774151	0	0	0	0	0	6106655	33210	0	0	0	307	4118429	25435	0	0	0	397	284719	122	0	0	0	0	0	59471

Table 62. Cell cost changes in raster dataset when the weight of criterion C7- "Maximise distance to natural protected areas" changes

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
-20	857205	0	0	0	0	0	6342034	26784	0	0	0	6876	3799524	24486	0	0	0	2680	282526	655	0	0	0	6	649	61487
-19	857205	0	0	0	0	0	6342034	26784	0	0	0	6876	3799524	24486	0	0	0	2680	282526	655	0	0	0	6	649	61487
-18	857205	0	0	0	0	0	6366057	2761	0	0	0	6876	3806337	17673	0	0	0	1931	283275	655	0	0	0	6	649	29902
-17	857205	0	0	0	0	0	6366057	2761	0	0	0	6876	3806337	17673	0	0	0	1931	283275	655	0	0	0	6	649	29902
-16	857205	0	0	0	0	0	6366057	2761	0	0	0	6876	3806337	17673	0	0	0	1931	283275	655	0	0	0	6	649	29902
-15	857205	0	0	0	0	0	6366057	2761	0	0	0	6876	3806337	17673	0	0	0	1931	283275	655	0	0	0	6	649	29902
-14	857205	0	0	0	0	0	6366057	2761	0	0	0	6876	3806337	17673	0	0	0	1931	283275	655	0	0	0	6	649	29902
-13	857205	0	0	0	0	0	6366057	2761	0	0	0	6876	3818887	5123	0	0	0	1931	283930	0	0	0	0	6	649	16697
-12	857205	0	0	0	0	0	6366057	2761	0	0	0	6876	3818885	5125	0	0	0	1931	283930	0	0	0	0	6	649	16699
-11	857205	0	0	0	0	0	6366057	2761	0	0	0	5918	3819845	5123	0	0	0	1931	283930	0	0	0	0	6	649	15739
-10	857205	0	0	0	0	0	6366068	2750	0	0	0	5918	3820683	4285	0	0	0	1931	283930	0	0	0	0	6	649	14890
-9	857205	0	0	0	0	0	6366068	2750	0	0	0	5918	3820681	4287	0	0	0	1931	283930	0	0	0	0	6	649	14892
-8	857205	0	0	0	0	0	6366068	2750	0	0	0	5918	3820683	4285	0	0	0	1931	283930	0	0	0	0	6	649	14890
-7	857205	0	0	0	0	0	6366081	2737	0	0	0	5918	3822717	2251	0	0	0	1931	283930	0	0	0	0	6	649	12843
-6	857205	0	0	0	0	0	6366081	2737	0	0	0	5918	3822717	2251	0	0	0	1931	283930	0	0	0	0	6	649	12843
-5	857205	0	0	0	0	0	6366081	2737	0	0	0	5918	3822717	2251	0	0	0	1931	283930	0	0	0	0	6	649	12843
-4	857205	0	0	0	0	0	6367726	1092	0	0	0	0	3828777	2109	0	0	0	1059	284802	0	0	0	0	0	655	4260
-3	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830886	0	0	0	0	1059	284802	0	0	0	0	0	655	1059
-2	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830886	0	0	0	0	1059	284802	0	0	0	0	0	655	1059
-1	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830886	0	0	0	0	0	285861	0	0	0	0	0	655	0
0	**857205**	**0**	**0**	**0**	**0**	**0**	**6368818**	**0**	**0**	**0**	**0**	**0**	**3830886**	**0**	**0**	**0**	**0**	**0**	**285861**	**0**	**0**	**0**	**0**	**0**	**655**	**0**

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
1	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830886	0	0	0	0	0	285861	0	0	0	0	0	655	0
2	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830886	0	0	0	0	0	285861	0	0	0	0	0	655	0
3	857205	0	0	0	0	0	6362087	6731	0	0	0	58385	3758715	13786	0	0	0	29934	255779	148	0	0	0	0	655	108984
4	857205	0	0	0	0	0	6362087	6731	0	0	0	58385	3758715	13786	0	0	0	29934	255779	148	0	0	0	0	655	108984
5	857205	0	0	0	0	0	6362087	6731	0	0	0	58385	3758713	13788	0	0	0	29934	255779	148	0	0	0	0	655	108986
6	857205	0	0	0	0	0	6362087	6731	0	0	0	61167	3755933	13786	0	0	0	46732	238981	148	0	0	0	0	655	128564
7	857205	0	0	0	0	0	6362087	6731	0	0	0	61167	3755933	13786	0	0	0	46732	238981	148	0	0	0	0	655	128564
8	857205	0	0	0	0	0	6362087	6731	0	0	0	61167	3755931	13788	0	0	0	46732	238981	148	0	0	0	0	655	128566
9	857205	0	0	0	0	0	6362087	6731	0	0	0	61167	3755933	13786	0	0	0	46732	238981	148	0	0	0	0	655	128564
10	857205	0	0	0	0	0	6362087	6731	0	0	0	125617	3691483	13786	0	0	0	75604	210109	148	0	0	0	0	655	221886
11	857205	0	0	0	0	0	6362087	6731	0	0	0	125617	3691483	13786	0	0	0	75604	210109	148	0	0	0	0	655	221886
12	857205	0	0	0	0	0	6362087	6731	0	0	0	125617	3691483	13786	0	0	0	75604	210109	148	0	0	0	0	655	221886
13	857205	0	0	0	0	0	6362087	6731	0	0	0	125617	3691483	13786	0	0	0	75604	210109	148	0	0	0	0	655	221886
14	857205	0	0	0	0	0	6362087	6731	0	0	0	125617	3691483	13786	0	0	0	75604	210109	148	0	0	0	0	655	221886
15	857205	0	0	0	0	0	6362087	6731	0	0	0	125617	3691483	13786	0	0	0	75945	209768	148	0	0	0	0	655	222227
16	857205	0	0	0	0	0	6362087	6731	0	0	0	125617	3691483	13786	0	0	0	75945	209768	148	0	0	0	0	655	222227
17	857205	0	0	0	0	0	6362087	6731	0	0	0	125617	3691483	13786	0	0	0	75945	209768	148	0	0	0	0	655	222227
18	857205	0	0	0	0	0	6362087	6731	0	0	0	125617	3691483	13786	0	0	0	75945	209768	148	0	0	0	0	655	222227
19	857205	0	0	0	0	0	6362087	6731	0	0	0	125617	3691483	13786	0	0	0	75946	209767	148	0	0	0	0	655	222228
20	857205	0	0	0	0	0	6362087	6731	0	0	0	125617	3691483	13786	0	0	0	75946	209767	148	0	0	0	0	655	222228

Table 63. Cell cost changes in raster dataset when the weight of criterion C8 – "Maximise distance to fragile water streams" changes

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
-20	857205	0	0	0	0	0	6367619	1199	0	0	0	58156	3769695	3035	0	0	0	30737	255124	0	0	0	0	0	655	93127
-19	857205	0	0	0	0	0	6367619	1199	0	0	0	58156	3769695	3035	0	0	0	30737	255124	0	0	0	0	0	655	93127
-18	857205	0	0	0	0	0	6367619	1199	0	0	0	58156	3769695	3035	0	0	0	30737	255124	0	0	0	0	0	655	93127
-17	857205	0	0	0	0	0	6367619	1199	0	0	0	58156	3769695	3035	0	0	0	30737	255124	0	0	0	0	0	655	93127
-16	857205	0	0	0	0	0	6367619	1199	0	0	0	58156	3769695	3035	0	0	0	30737	255124	0	0	0	0	0	655	93127
-15	857205	0	0	0	0	0	6367619	1199	0	0	0	58156	3769695	3035	0	0	0	29988	255873	0	0	0	0	0	655	92378
-14	857205	0	0	0	0	0	6367619	1199	0	0	0	58156	3769695	3035	0	0	0	29988	255873	0	0	0	0	0	655	92378
-13	857205	0	0	0	0	0	6367619	1199	0	0	0	57136	3770715	3035	0	0	0	29890	255971	0	0	0	0	0	655	91260
-12	857205	0	0	0	0	0	6367619	1199	0	0	0	57136	3770715	3035	0	0	0	29890	255971	0	0	0	0	0	655	91260
-11	857205	0	0	0	0	0	6367619	1199	0	0	0	57136	3770715	3035	0	0	0	29890	255971	0	0	0	0	0	655	91260
-10	857205	0	0	0	0	0	6367619	1199	0	0	0	57136	3770715	3035	0	0	0	29890	255971	0	0	0	0	0	655	91260
-9	857205	0	0	0	0	0	6367619	1199	0	0	0	57136	3770715	3035	0	0	0	29890	255971	0	0	0	0	0	655	91260
-8	857205	0	0	0	0	0	6367726	1092	0	0	0	57136	3771553	2197	0	0	0	29890	255971	0	0	0	0	0	655	90315
-7	857205	0	0	0	0	0	6367726	1092	0	0	0	57136	3771641	2109	0	0	0	29890	255971	0	0	0	0	0	655	90227
-6	857205	0	0	0	0	0	6368818	0	0	0	0	57136	3773750	0	0	0	0	29890	255971	0	0	0	0	0	655	87026
-5	857205	0	0	0	0	0	6368818	0	0	0	0	57136	3773750	0	0	0	0	29890	255971	0	0	0	0	0	655	87026
-4	857205	0	0	0	0	0	6368818	0	0	0	0	55973	3774913	0	0	0	0	432	285429	0	0	0	0	0	655	56405
-3	857205	0	0	0	0	0	6368818	0	0	0	0	55973	3774913	0	0	0	0	432	285429	0	0	0	0	0	655	56405
-2	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830886	0	0	0	0	0	285861	0	0	0	0	0	655	0
-1	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830886	0	0	0	0	0	285861	0	0	0	0	0	655	0
0	**857205**	**0**	**0**	**0**	**0**	**0**	**6368818**	**0**	**0**	**0**	**0**	**0**	**3830886**	**0**	**0**	**0**	**0**	**0**	**285861**	**0**	**0**	**0**	**0**	**0**	**655**	**0**

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
1	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830884	2	0	0	0	0	285861	0	0	0	0	0	655	2
2	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830884	2	0	0	0	0	285861	0	0	0	0	0	655	2
3	857205	0	0	0	0	0	6368479	339	0	0	0	0	3830742	144	0	0	0	1059	284802	0	0	0	0	0	655	1542
4	857205	0	0	0	0	0	6368479	339	0	0	0	0	3830742	144	0	0	0	1059	284802	0	0	0	0	0	655	1542
5	857205	0	0	0	0	0	6367173	1645	0	0	0	0	3830742	144	0	0	0	1931	283930	0	0	0	0	6	649	3726
6	857205	0	0	0	0	0	6367173	1645	0	0	0	0	3830742	144	0	0	0	1931	283930	0	0	0	0	6	649	3726
7	857205	0	0	0	0	0	6367173	1645	0	0	0	0	3830742	144	0	0	0	1931	283930	0	0	0	0	6	649	3726
8	857205	0	0	0	0	0	6367173	1645	0	0	0	0	3830742	144	0	0	0	1931	283930	0	0	0	0	6	649	3726
9	857205	0	0	0	0	0	6367173	1645	0	0	0	5918	3824824	144	0	0	0	1931	283930	0	0	0	0	6	649	9644
10	857205	0	0	0	0	0	6367173	1645	0	0	0	5918	3824824	144	0	0	0	1931	283930	0	0	0	0	6	649	9644
11	857205	0	0	0	0	0	6367173	1645	0	0	0	5918	3824824	144	0	0	0	1931	283930	0	0	0	0	6	649	9644
12	857205	0	0	0	0	0	6367173	1645	0	0	0	5918	3824824	144	0	0	0	1931	283930	0	0	0	0	6	649	9644
13	857205	0	0	0	0	0	6367173	1645	0	0	0	5918	3824824	144	0	0	0	3245	282616	0	0	0	0	6	649	10958
14	857205	0	0	0	0	0	6367173	1645	0	0	0	5918	3824824	144	0	0	0	3245	282616	0	0	0	0	6	649	10958
15	857205	0	0	0	0	0	6367173	1645	0	0	0	5918	3824824	144	0	0	0	3245	282616	0	0	0	0	6	649	10958
16	857205	0	0	0	0	0	6367173	1645	0	0	0	5918	3824824	144	0	0	0	3245	282616	0	0	0	0	6	649	10958
17	857205	0	0	0	0	0	6367173	1645	0	0	0	38690	3792052	144	0	0	0	32092	253769	0	0	0	0	6	649	72577
18	857205	0	0	0	0	0	6366554	2264	0	0	0	38690	3792049	147	0	0	0	32092	253769	0	0	0	0	6	649	73199
19	857205	0	0	0	0	0	6366554	2264	0	0	0	38690	3792049	147	0	0	0	32092	253769	0	0	0	0	6	649	73199
20	857205	0	0	0	0	0	6366554	2264	0	0	0	38690	3792049	147	0	0	0	32092	253769	0	0	0	0	6	649	73199

Table 64. Cell cost changes in raster dataset when the weight of criterion C9 – "Maximise distance to surface waters – dams and ponds" changes

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
-20	857205	0	0	0	0	0	6356578	12240	0	0	0	93363	3708085	29438	0	0	0	45989	239002	870	0	0	0	0	655	181900
-19	857205	0	0	0	0	0	6356578	12240	0	0	0	92912	3708536	29438	0	0	0	45838	239153	870	0	0	0	0	655	181298
-18	857205	0	0	0	0	0	6356578	12240	0	0	0	36803	3767905	26178	0	0	0	45690	240023	148	0	0	0	0	655	121059
-17	857205	0	0	0	0	0	6356578	12240	0	0	0	36803	3769078	25005	0	0	0	45690	240023	148	0	0	0	0	655	119886
-16	857205	0	0	0	0	0	6358362	10456	0	0	0	36803	3776942	17141	0	0	0	45690	240023	148	0	0	0	0	655	110238
-15	857205	0	0	0	0	0	6359684	9134	0	0	0	36803	3776965	17118	0	0	0	45690	240023	148	0	0	0	0	655	108893
-14	857205	0	0	0	0	0	6360337	8481	0	0	0	36803	3777717	16366	0	0	0	45690	240023	148	0	0	0	0	655	107488
-13	857205	0	0	0	0	0	6360337	8481	0	0	0	36803	3777717	16366	0	0	0	45690	240023	148	0	0	0	0	655	107488
-12	857205	0	0	0	0	0	6361748	7070	0	0	0	36803	3777730	16353	0	0	0	45689	240024	148	0	0	0	0	655	106063
-11	857205	0	0	0	0	0	6361748	7070	0	0	0	36803	3777730	16353	0	0	0	45689	240024	148	0	0	0	0	655	106063
-10	857205	0	0	0	0	0	6361748	7070	0	0	0	36803	3777730	16353	0	0	0	45689	240024	148	0	0	0	0	655	106063
-9	857205	0	0	0	0	0	6361748	7070	0	0	0	36803	3780153	13930	0	0	0	45689	240024	148	0	0	0	0	655	103640
-8	857205	0	0	0	0	0	6361748	7070	0	0	0	36803	3780153	13930	0	0	0	45689	240024	148	0	0	0	0	655	103640
-7	857205	0	0	0	0	0	6361748	7070	0	0	0	34021	3782935	13930	0	0	0	29447	256266	148	0	0	0	0	655	84616
-6	857205	0	0	0	0	0	6361748	7070	0	0	0	34021	3782935	13930	0	0	0	29447	256266	148	0	0	0	0	655	84616
-5	857205	0	0	0	0	0	6361748	7070	0	0	0	1249	3815707	13930	0	0	0	600	285113	148	0	0	0	0	655	22997
-4	857205	0	0	0	0	0	6361748	7070	0	0	0	1249	3815707	13930	0	0	0	600	285113	148	0	0	0	0	655	22997
-3	857205	0	0	0	0	0	6361748	7070	0	0	0	1249	3815707	13930	0	0	0	44	285669	148	0	0	0	0	655	22441
-2	857205	0	0	0	0	0	6362183	6635	0	0	0	1249	3815849	13788	0	0	0	44	285669	148	0	0	0	0	655	21864
-1	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830884	2	0	0	0	0	285861	0	0	0	0	0	655	2
0	**857205**	**0**	**0**	**0**	**0**	**0**	**6368818**	**0**	**0**	**0**	**0**	**0**	**3830886**	**0**	**0**	**0**	**0**	**0**	**285861**	**0**	**0**	**0**	**0**	**0**	**655**	**0**

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
1	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830886	0	0	0	0	0	285861	0	0	0	0	0	655	0
2	857205	0	0	0	0	0	6368818	0	0	0	0	55973	3774913	0	0	0	0	1491	284370	0	0	0	0	0	655	57464
3	857205	0	0	0	0	0	6367726	1092	0	0	0	61891	3766886	2109	0	0	0	1491	284370	0	0	0	0	0	655	66583
4	857205	0	0	0	0	0	6367726	1092	0	0	0	61891	3766886	2109	0	0	0	1491	284370	0	0	0	0	0	655	66583
5	857205	0	0	0	0	0	6367726	1092	0	0	0	61891	3766249	2746	0	0	0	2240	283621	0	0	0	0	0	655	67969
6	857205	0	0	0	0	0	6367715	1103	0	0	0	61891	3765411	3584	0	0	0	2240	283621	0	0	0	0	0	655	68818
7	857205	0	0	0	0	0	6367715	1103	0	0	0	61891	3765323	3672	0	0	0	2240	283621	0	0	0	0	0	655	68906
8	857205	0	0	0	0	0	6367715	1103	0	0	0	61891	3765323	3672	0	0	0	2240	283621	0	0	0	0	0	655	68906
9	857205	0	0	0	0	0	6367702	1116	0	0	0	61891	3763926	5069	0	0	0	2240	283621	0	0	0	0	0	655	70316
10	857205	0	0	0	0	0	6351904	16914	0	0	0	61891	3762622	6373	0	0	0	2240	283621	0	0	0	0	0	655	87418
11	857205	0	0	0	0	0	6351904	16914	0	0	0	61891	3762622	6373	0	0	0	2240	283621	0	0	0	0	0	655	87418
12	857205	0	0	0	0	0	6351904	16914	0	0	0	72351	3750728	7807	0	0	0	18294	267567	0	0	0	0	0	655	115366
13	857205	0	0	0	0	0	6351904	16914	0	0	0	72351	3750728	7807	0	0	0	18294	267567	0	0	0	0	0	655	115366
14	857205	0	0	0	0	0	6351904	16914	0	0	0	72372	3750707	7807	0	0	0	19711	266150	0	0	0	0	0	655	116804
15	857205	0	0	0	0	0	6351904	16914	0	0	0	72440	3750639	7807	0	0	0	19711	266150	0	0	0	0	0	655	116872
16	857205	0	0	0	0	0	6349396	19422	0	0	0	72440	3747024	11422	0	0	0	19711	266150	0	0	0	0	0	655	122995
17	857205	0	0	0	0	0	6349396	19422	0	0	0	72440	3747024	11422	0	0	0	19711	266150	0	0	0	0	0	655	122995
18	857205	0	0	0	0	0	6346682	22136	0	0	0	72440	3741680	16766	0	0	0	19711	266150	0	0	0	0	0	655	131053
19	857205	0	0	0	0	0	6346682	22136	0	0	0	72440	3741664	16782	0	0	0	19711	266150	0	0	0	0	0	655	131069
20	857205	0	0	0	0	0	6346682	22136	0	0	0	72440	3729114	29332	0	0	0	19711	265495	655	0	0	0	0	655	144274

Table 65. Cell cost changes in raster dataset when the weight of criterion C10 – "Maximise distance to ground waters" changes

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
-20	857205	0	0	0	0	0	6367512	1306	0	0	0	94732	3736154	0	0	0	0	33160	252701	0	0	0	0	6	649	129204
-19	857205	0	0	0	0	0	6367512	1306	0	0	0	94732	3736154	0	0	0	0	33160	252701	0	0	0	0	6	649	129204
-18	857205	0	0	0	0	0	6367512	1306	0	0	0	94732	3736154	0	0	0	0	33160	252701	0	0	0	0	6	649	129204
-17	857205	0	0	0	0	0	6367512	1306	0	0	0	94732	3736154	0	0	0	0	33160	252701	0	0	0	0	6	649	129204
-16	857205	0	0	0	0	0	6368818	0	0	0	0	94732	3736154	0	0	0	0	32288	253573	0	0	0	0	0	655	127020
-15	857205	0	0	0	0	0	6368818	0	0	0	0	94732	3736154	0	0	0	0	32288	253573	0	0	0	0	0	655	127020
-14	857205	0	0	0	0	0	6368818	0	0	0	0	94732	3736154	0	0	0	0	32288	253573	0	0	0	0	0	655	127020
-13	857205	0	0	0	0	0	6368818	0	0	0	0	94732	3736154	0	0	0	0	32288	253573	0	0	0	0	0	655	127020
-12	857205	0	0	0	0	0	6368818	0	0	0	0	94732	3736154	0	0	0	0	30974	254887	0	0	0	0	0	655	125706
-11	857205	0	0	0	0	0	6368818	0	0	0	0	94732	3736154	0	0	0	0	30974	254887	0	0	0	0	0	655	125706
-10	857205	0	0	0	0	0	6368818	0	0	0	0	63054	3767832	0	0	0	0	30949	254912	0	0	0	0	0	655	94003
-9	857205	0	0	0	0	0	6368818	0	0	0	0	63054	3767832	0	0	0	0	30949	254912	0	0	0	0	0	655	94003
-8	857205	0	0	0	0	0	6368818	0	0	0	0	61891	3768995	0	0	0	0	1491	284370	0	0	0	0	0	655	63382
-7	857205	0	0	0	0	0	6368818	0	0	0	0	61891	3768995	0	0	0	0	1491	284370	0	0	0	0	0	655	63382
-6	857205	0	0	0	0	0	6368818	0	0	0	0	61891	3768995	0	0	0	0	1491	284370	0	0	0	0	0	655	63382
-5	857205	0	0	0	0	0	6368818	0	0	0	0	55973	3774913	0	0	0	0	1491	284370	0	0	0	0	0	655	57464
-4	857205	0	0	0	0	0	6368818	0	0	0	0	55973	3774913	0	0	0	0	432	285429	0	0	0	0	0	655	56405
-3	857205	0	0	0	0	0	6368818	0	0	0	0	55973	3774913	0	0	0	0	432	285429	0	0	0	0	0	655	56405
-2	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830886	0	0	0	0	0	285861	0	0	0	0	0	655	0
-1	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830886	0	0	0	0	0	285861	0	0	0	0	0	655	0
0	**857205**	**0**	**0**	**0**	**0**	**0**	**6368818**	**0**	**0**	**0**	**0**	**0**	**3830886**	**0**	**0**	**0**	**0**	**0**	**285861**	**0**	**0**	**0**	**0**	**0**	**655**	**0**

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
1	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830884	2	0	0	0	0	285861	0	0	0	0	0	655	2
2	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830884	2	0	0	0	0	285861	0	0	0	0	0	655	2
3	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830884	2	0	0	0	0	285861	0	0	0	0	0	655	2
4	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830884	2	0	0	0	0	285861	0	0	0	0	0	655	2
5	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830884	2	0	0	0	0	285861	0	0	0	0	0	655	2
6	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830884	2	0	0	0	0	285861	0	0	0	0	0	655	2
7	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830884	2	0	0	0	0	285861	0	0	0	0	0	655	2
8	857205	0	0	0	0	0	6368818	0	0	0	0	0	3830884	2	0	0	0	0	285861	0	0	0	0	0	655	2
9	857205	0	0	0	0	0	6362183	6635	0	0	0	1249	3815849	13788	0	0	0	44	285669	148	0	0	0	0	655	21864
10	857205	0	0	0	0	0	6362183	6635	0	0	0	1249	3815849	13788	0	0	0	44	285669	148	0	0	0	0	655	21864
11	857205	0	0	0	0	0	6362183	6635	0	0	0	1249	3815849	13788	0	0	0	44	285669	148	0	0	0	0	655	21864
12	857205	0	0	0	0	0	6362183	6635	0	0	0	1249	3815849	13788	0	0	0	44	285669	148	0	0	0	0	655	21864
13	857205	0	0	0	0	0	6362183	6635	0	0	0	1249	3815849	13788	0	0	0	44	285669	148	0	0	0	0	655	21864
14	857205	0	0	0	0	0	6362183	6635	0	0	0	1249	3815849	13788	0	0	0	44	285669	148	0	0	0	0	655	21864
15	857205	0	0	0	0	0	6362183	6635	0	0	0	1249	3815849	13788	0	0	0	44	285669	148	0	0	0	0	655	21864
16	857205	0	0	0	0	0	6361833	6985	0	0	0	1249	3814869	14768	0	0	0	44	285669	148	0	0	0	0	655	23194
17	857205	0	0	0	0	0	6361833	6985	0	0	0	1249	3814869	14768	0	0	0	44	285669	148	0	0	0	0	655	23194
18	857205	0	0	0	0	0	6361833	6985	0	0	0	1249	3814869	14768	0	0	0	44	285669	148	0	0	0	0	655	23194
19	857205	0	0	0	0	0	6361833	6985	0	0	0	1249	3814869	14768	0	0	0	44	285669	148	0	0	0	0	655	23194
20	857205	0	0	0	0	0	6361833	6985	0	0	0	1249	3814869	14768	0	0	0	44	285669	148	0	0	0	0	655	23194

Table 66. Cell cost changes in raster dataset when the weight of criterion C11 – "Prioritise arable, grazing, forest and built-up land" changes

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
-20	144535	0	0	0	0	0	3626260	123159	0	0	0	291793	6263986	14728	0	0	0	177745	700405	0	0	0	0	716	98	608141
-19	144535	0	0	0	0	0	3626260	123159	0	0	0	291793	6263986	14728	0	0	0	177745	700405	0	0	0	0	716	98	608141
-18	144535	0	0	0	0	0	3626260	123159	0	0	0	291793	6263986	14728	0	0	0	177745	700405	0	0	0	0	716	98	608141
-17	144535	0	0	0	0	0	3626260	123159	0	0	0	291793	6263986	14728	0	0	0	177745	700405	0	0	0	0	716	98	608141
-16	144535	0	0	0	0	0	3626260	123159	0	0	0	290926	6264853	14728	0	0	0	162493	715657	0	0	0	0	376	438	591682
-15	144535	0	0	0	0	0	3626260	123159	0	0	0	290926	6264853	14728	0	0	0	162493	715657	0	0	0	0	376	438	591682
-14	144535	0	0	0	0	0	3626260	123159	0	0	0	290926	6264853	14728	0	0	0	162493	715657	0	0	0	0	376	438	591682
-13	144535	0	0	0	0	0	3626260	123159	0	0	0	290926	6264853	14728	0	0	0	162493	715657	0	0	0	0	376	438	591682
-12	144535	0	0	0	0	0	3641447	107972	0	0	0	290926	6268598	10983	0	0	0	162493	715657	0	0	0	0	376	438	572750
-11	144535	0	0	0	0	0	3641447	107972	0	0	0	290926	6268598	10983	0	0	0	162493	715657	0	0	0	0	376	438	572750
-10	144535	0	0	0	0	0	3641447	107972	0	0	0	290926	6268598	10983	0	0	0	162493	715657	0	0	0	0	376	438	572750
-9	144535	0	0	0	0	0	3641447	107972	0	0	0	290926	6268598	10983	0	0	0	162493	715657	0	0	0	0	376	438	572750
-8	144535	0	0	0	0	0	3641447	107972	0	0	0	290926	6268598	10983	0	0	0	153649	724501	0	0	0	0	0	814	563530
-7	144535	0	0	0	0	0	3641447	107972	0	0	0	290926	6268598	10983	0	0	0	153649	724501	0	0	0	0	0	814	563530
-6	144535	0	0	0	0	0	3641447	107972	0	0	0	290926	6268598	10983	0	0	0	153649	724501	0	0	0	0	0	814	563530
-5	144535	0	0	0	0	0	3641447	107972	0	0	0	290926	6268598	10983	0	0	0	153649	724501	0	0	0	0	0	814	563530
-4	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321
-3	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321
-2	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321
-1	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
0	**144535**	**0**	**0**	**0**	**0**	**0**	**3749419**	**0**	**0**	**0**	**0**	**0**	**6570507**	**0**	**0**	**0**	**0**	**0**	**878150**	**0**	**0**	**0**	**0**	**0**	**814**	**0**

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
1	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
2	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
3	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
4	144535	0	0	0	0	0	3749419	0	0	0	0	1606	6529499	39402	0	0	0	8	877853	289	0	0	0	0	814	41305
5	144535	0	0	0	0	0	3749419	0	0	0	0	1606	6529499	39402	0	0	0	8	877853	289	0	0	0	0	814	41305
6	144535	0	0	0	0	0	3749419	0	0	0	0	1606	6529499	39402	0	0	0	8	877853	289	0	0	0	0	814	41305
7	144535	0	0	0	0	0	3749419	0	0	0	0	1606	6529499	39402	0	0	0	8	877853	289	0	0	0	0	814	41305
8	144535	0	0	0	0	0	3749419	0	0	0	0	10386	4409182	2150939	0	0	0	8	870030	8112	0	0	0	0	814	2169445
9	144535	0	0	0	0	0	3749419	0	0	0	0	10386	4409182	2150939	0	0	0	8	870030	8112	0	0	0	0	814	2169445
10	144535	0	0	0	0	0	3749419	0	0	0	0	10386	4409182	2150939	0	0	0	8	870030	8112	0	0	0	0	814	2169445
11	144535	0	0	0	0	0	3749419	0	0	0	0	10386	4409182	2150939	0	0	0	8	870030	8112	0	0	0	0	814	2169445
12	144535	0	0	0	0	0	3749419	0	0	0	0	10386	4409182	2150939	0	0	0	8	870030	8112	0	0	0	0	814	2169445
13	144535	0	0	0	0	0	3749419	0	0	0	0	10386	4409182	2150939	0	0	0	8	870030	8112	0	0	0	0	814	2169445
14	144535	0	0	0	0	0	3749419	0	0	0	0	10386	4409182	2150939	0	0	0	8	870030	8112	0	0	0	0	814	2169445
15	144535	0	0	0	0	0	3749419	0	0	0	0	10386	4409182	2150939	0	0	0	8	870030	8112	0	0	0	0	814	2169445
16	144535	0	0	0	0	0	3749419	0	0	0	0	10386	4409182	2150939	0	0	0	8	870030	8112	0	0	0	0	814	2169445
17	144535	0	0	0	0	0	3749419	0	0	0	0	10386	4409182	2150939	0	0	0	8	870030	8112	0	0	0	0	814	2169445
18	144535	0	0	0	0	0	3749419	0	0	0	0	10386	4409182	2150939	0	0	0	8	870030	8112	0	0	0	0	814	2169445
19	144535	0	0	0	0	0	3749419	0	0	0	0	10386	4409182	2150939	0	0	0	8	870030	8112	0	0	0	0	814	2169445
20	144535	0	0	0	0	0	3749419	0	0	0	0	10386	4409182	2150939	0	0	0	8	870030	8112	0	0	0	0	814	2169445

Table 67. Cell cost changes in raster dataset when the weight of criterion C12 – "Maximise distance to residential areas to reduce air pollution" changes

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
-20	144535	0	0	0	0	0	3749419	0	0	0	0	1606	6529499	39402	0	0	0	8	877853	289	0	0	0	0	814	41305
-19	144535	0	0	0	0	0	3749419	0	0	0	0	1606	6529499	39402	0	0	0	8	877853	289	0	0	0	0	814	41305
-18	144535	0	0	0	0	0	3749419	0	0	0	0	1606	6529499	39402	0	0	0	8	877853	289	0	0	0	0	814	41305
-17	144535	0	0	0	0	0	3749419	0	0	0	0	1606	6529499	39402	0	0	0	8	877853	289	0	0	0	0	814	41305
-16	144535	0	0	0	0	0	3749419	0	0	0	0	1606	6529499	39402	0	0	0	8	877853	289	0	0	0	0	814	41305
-15	144535	0	0	0	0	0	3749419	0	0	0	0	1606	6529499	39402	0	0	0	8	877853	289	0	0	0	0	814	41305
-14	144535	0	0	0	0	0	3749419	0	0	0	0	1606	6529499	39402	0	0	0	8	877853	289	0	0	0	0	814	41305
-13	144535	0	0	0	0	0	3749419	0	0	0	0	1606	6529499	39402	0	0	0	8	877853	289	0	0	0	0	814	41305
-12	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-11	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-10	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-9	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-8	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-7	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-6	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-5	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-4	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
-3	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
-2	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
-1	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
0	**144535**	**0**	**0**	**0**	**0**	**0**	**3749419**	**0**	**0**	**0**	**0**	**0**	**6570507**	**0**	**0**	**0**	**0**	**0**	**878150**	**0**	**0**	**0**	**0**	**0**	**814**	**0**

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
1	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
2	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
3	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
4	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
5	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
6	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321
7	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321
8	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321
9	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321
10	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321
11	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321
12	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321
13	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321
14	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321
15	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321
16	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321
17	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321
18	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321
19	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321
20	144535	0	0	0	0	0	3746110	3309	0	0	0	0	6570495	12	0	0	0	0	878150	0	0	0	0	0	814	3321

Table 68. Cell cost changes in raster dataset when the weight of criterion C13 – "Maximise distance to residential areas to reduce air pollution" changes

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
-20	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-19	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-18	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-17	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-16	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-15	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-14	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-13	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-12	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-11	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-10	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-9	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-8	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-7	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-6	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-5	144535	0	0	0	0	0	3749419	0	0	0	0	0	6531105	39402	0	0	0	0	877861	289	0	0	0	0	814	39691
-4	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
-3	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
-2	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
-1	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
0	**144535**	**0**	**0**	**0**	**0**	**0**	**3749419**	**0**	**0**	**0**	**0**	**0**	**6570507**	**0**	**0**	**0**	**0**	**0**	**878150**	**0**	**0**	**0**	**0**	**0**	**814**	**0**

PC	11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55	TC
1	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
2	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
3	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
4	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
5	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
6	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
7	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
8	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
9	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
10	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
11	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
12	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
13	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
14	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
15	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
16	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
17	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
18	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
19	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0
20	144535	0	0	0	0	0	3749419	0	0	0	0	0	6570507	0	0	0	0	0	878150	0	0	0	0	0	814	0

13 Appendix IV– Spatial change of sensitive criteria

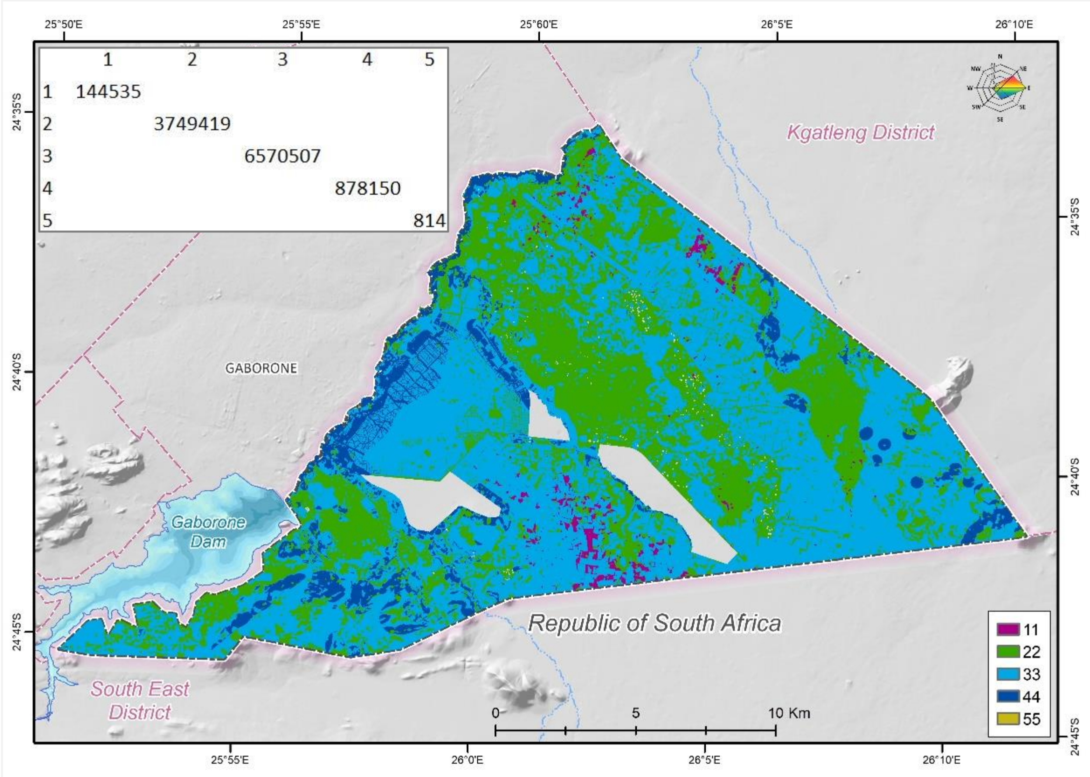


Figure 81. Base case scenario with no cell changes for criterion C11 (PC= 0%)

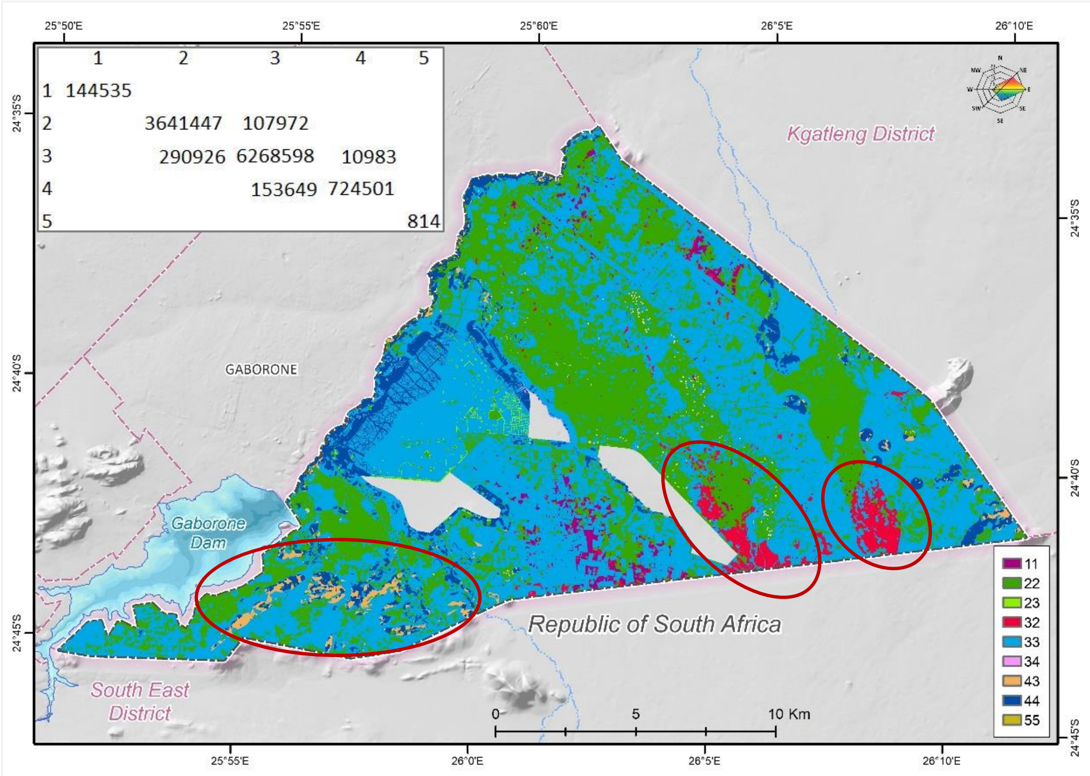


Figure 82. Scenario where the cells changes started to be significant for criterion C11 (PC = -5%)

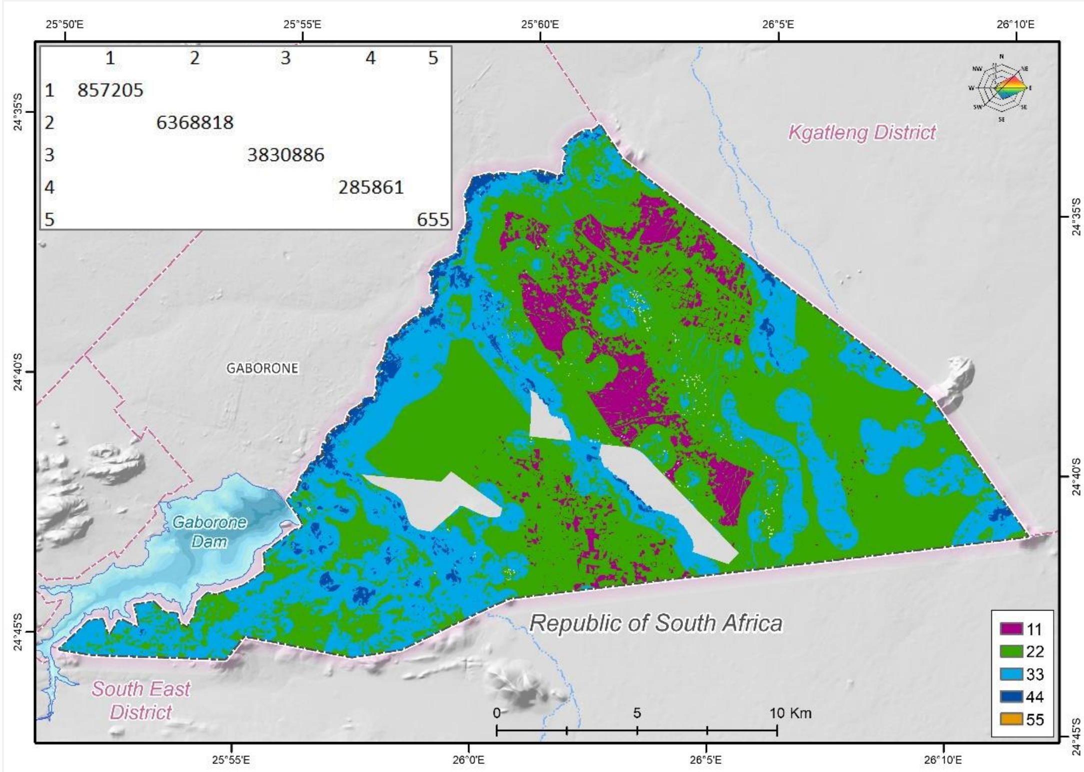


Figure 83. Base case scenario with no cell changes for criterion C7 (PC = 0%)

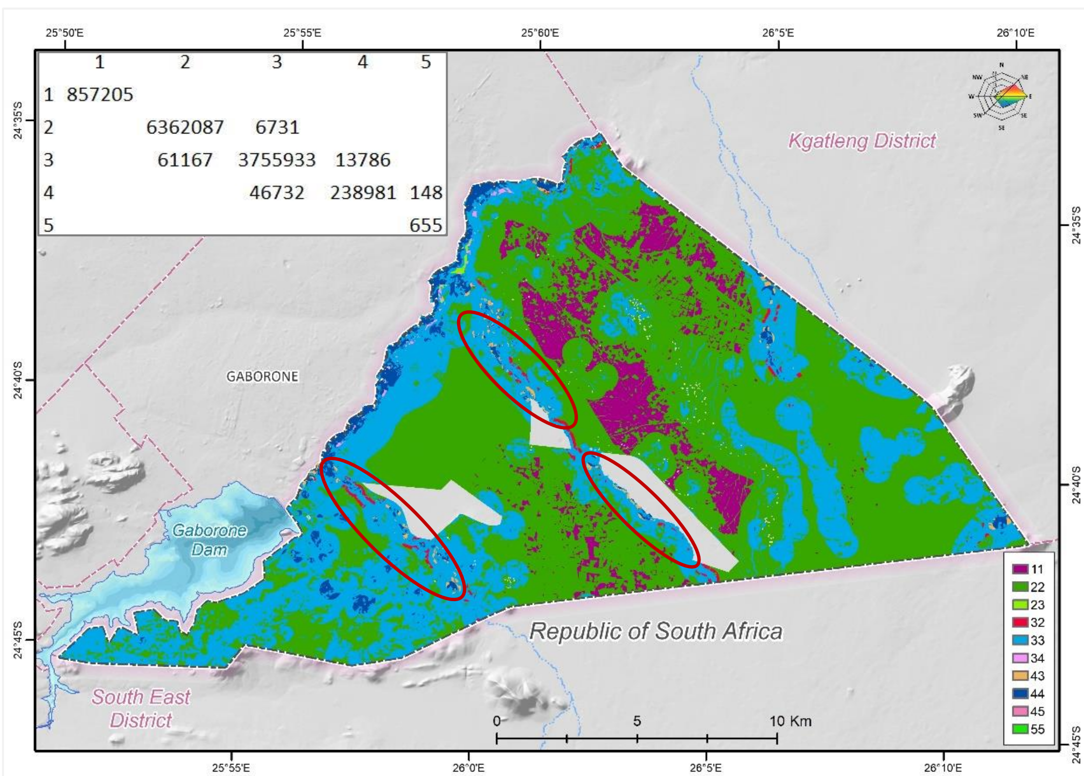


Figure 84. Scenario where the cells changes started to be significant for criterion C7 (PC= 6%)

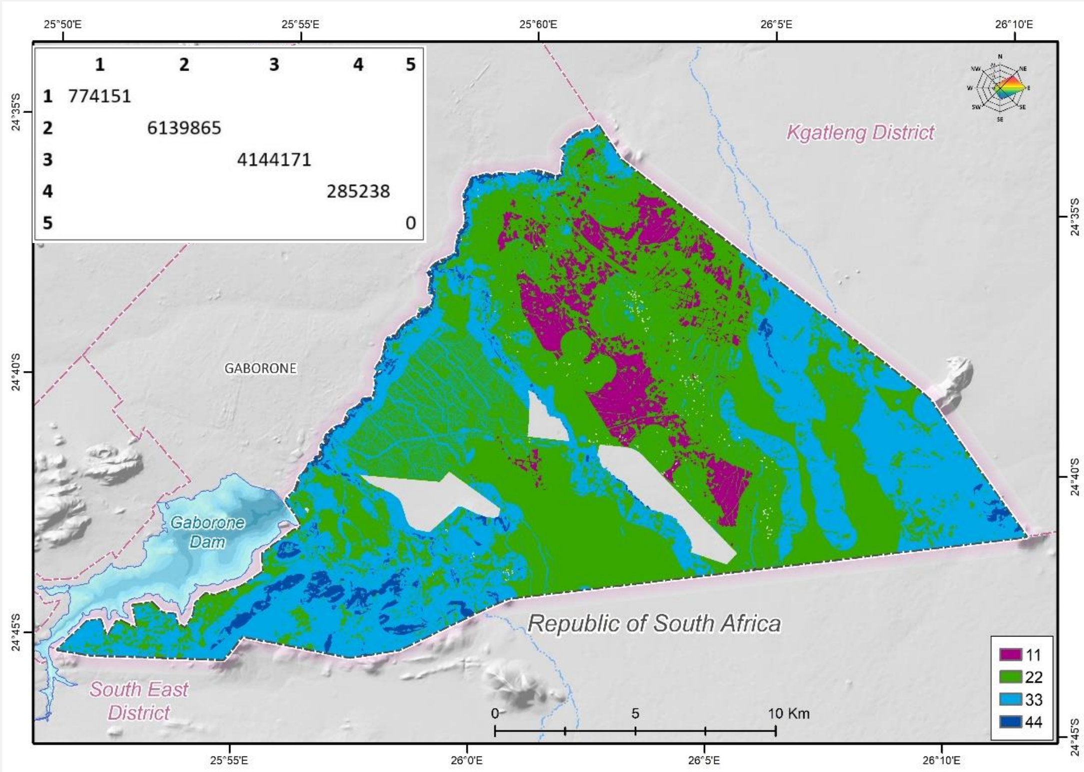


Figure 85. Base case scenario with no cell changes for criterion C1 (PC = 0%)

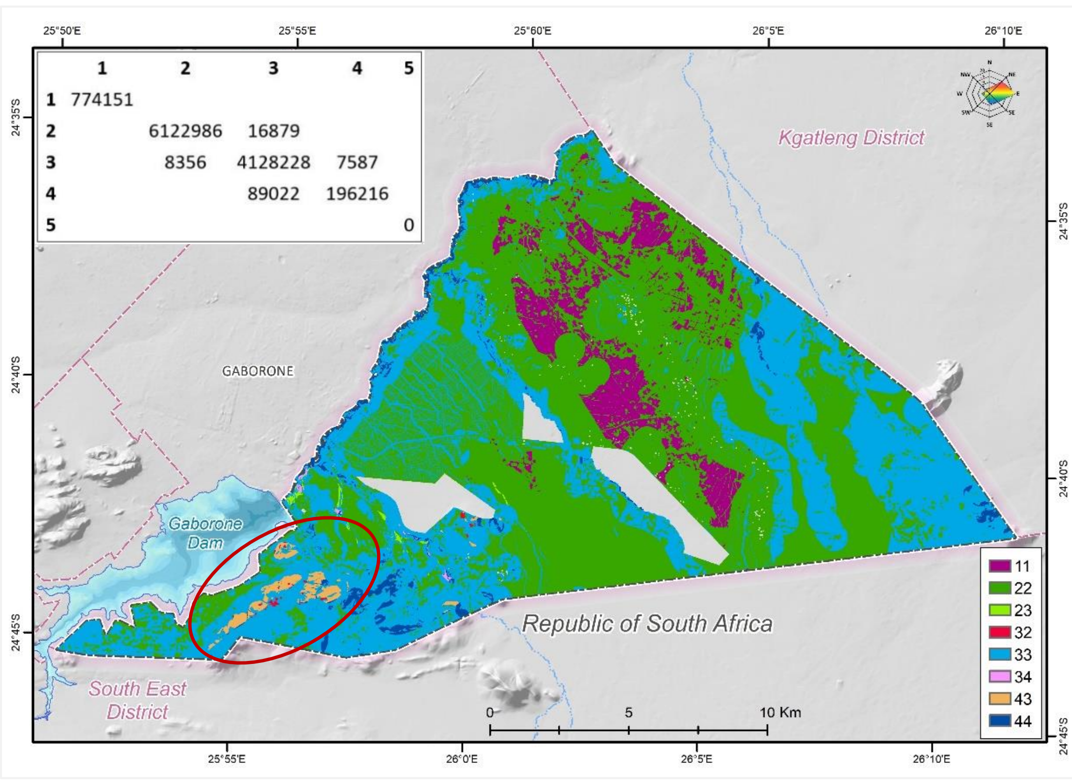


Figure 86. Scenario where the cells changes started to be significant for criterion C1 (PC= -8%)

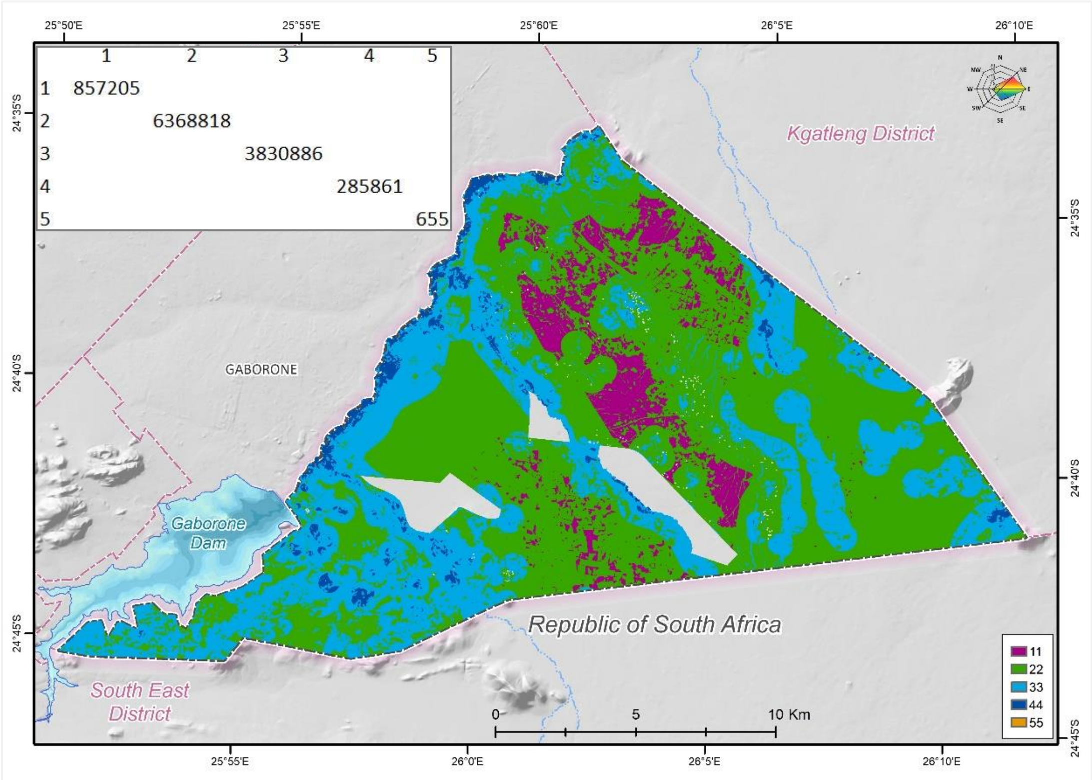


Figure 87. Base case scenario with no cell changes for criterion C10 (PC= 0%)

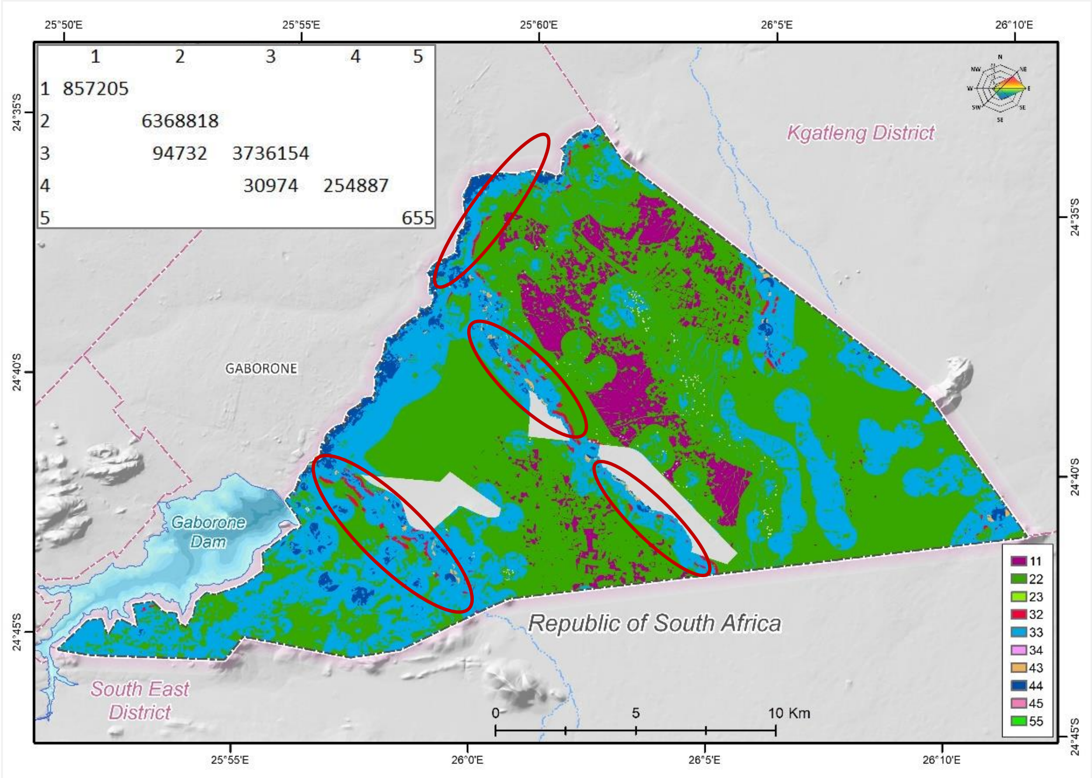


Figure 88. Scenario where the cells changes started to be significant for criterion C10 (PC = -11%)

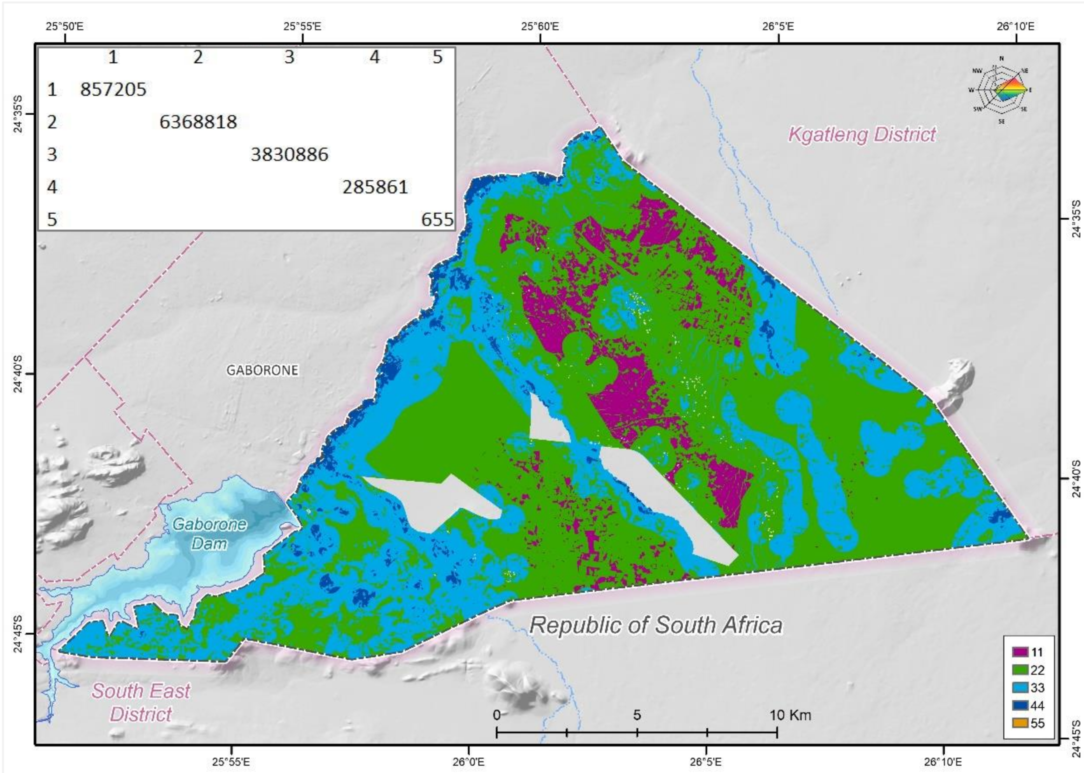


Figure 89. Base case scenario with no cell changes for criterion C9 (PC = 0%)

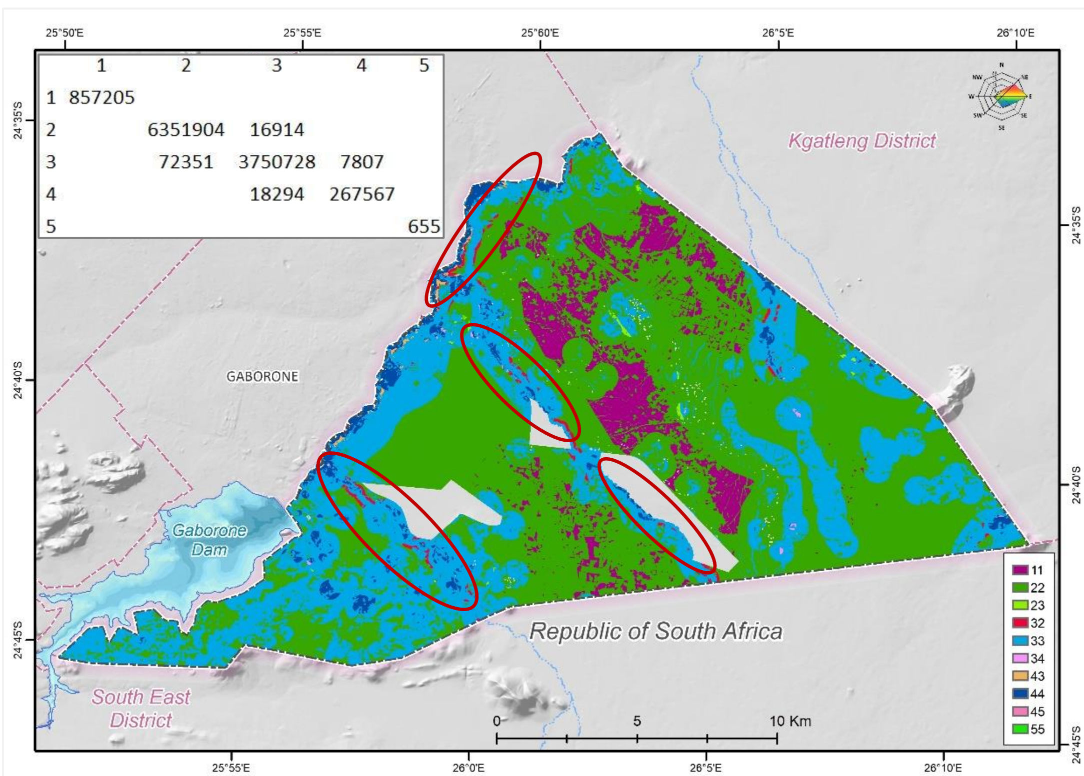


Figure 90. Scenario where the cells changes started to be significant for criterion C9 (PC= 12%)

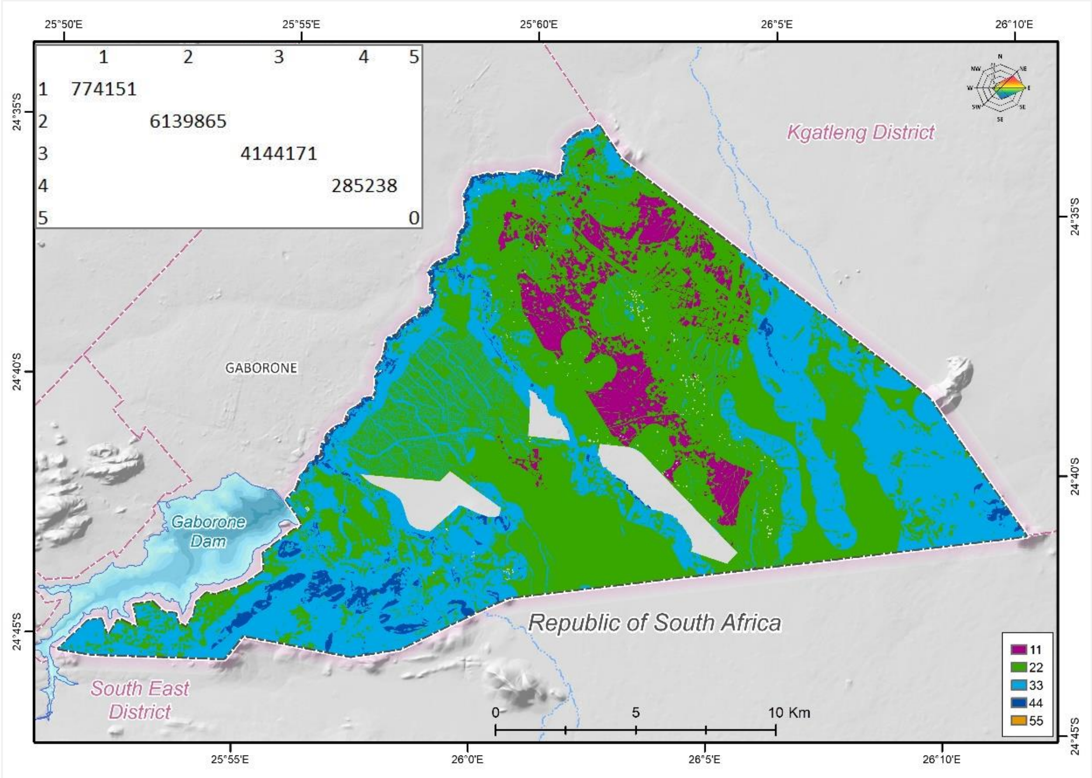


Figure 91. Base case scenario with no cell changes for criterion C3 (PC = 0%)

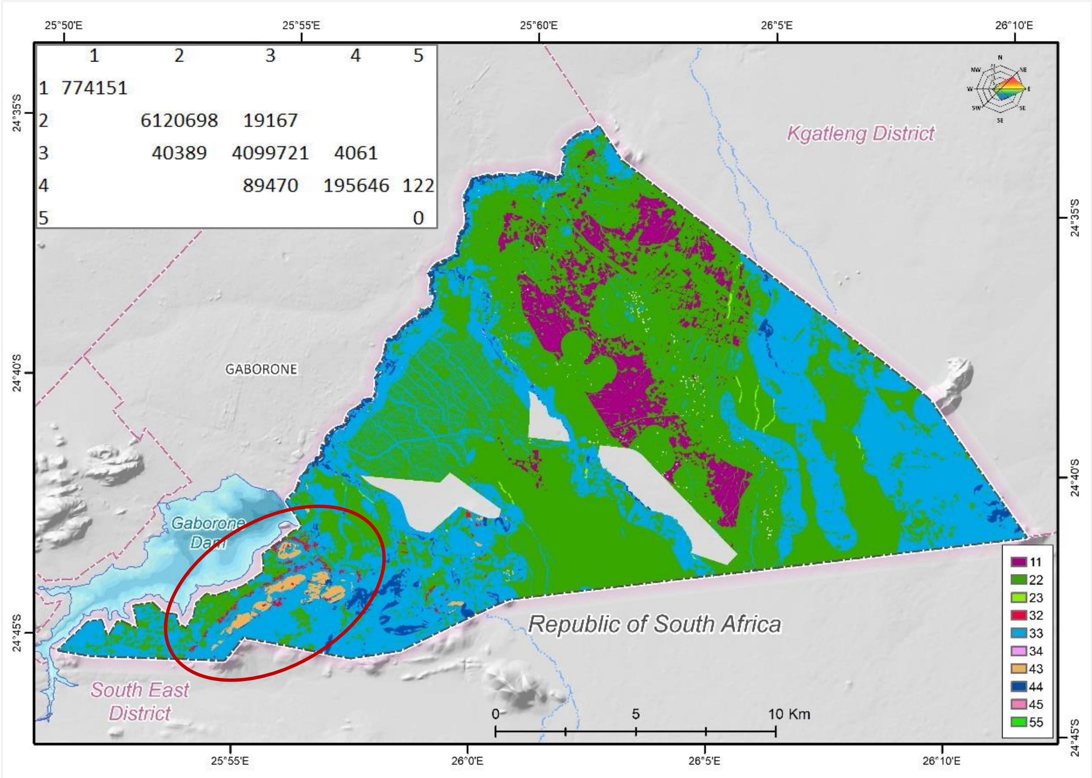


Figure 92. Scenario where the cells changes started to be significant for criterion C3 (PC= 16%)

14 Appendix V – Python script

```python
# Import system modules
import math
import arcpy
from arcpy import env
from arcpy.sa import *
import csv
import decimal
from decimal import *


#-------------------------------------------------

# Set files that are input in the model

# ECONOMIC criteria
inpSlope = "E:\\Milan_GIS\\MCD_Baza\\Tlokweng_MCD.gdb\\Slope_WA"
inpRoads = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\ProcessedData\\Roads_line_buffer\\Roads.shp"
inpDrainage = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\ProcessedData\\Strah_Diss.shp"
inpFlooding = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\ProcessedData\\flood_fin_rec"
inpGeology = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\ProcessedData\\Geology_Tlokw.shp"
inpSoil = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\ProcessedData\\Soil_Dissolved.shp"

# ENVIRONMENTAL criteria
inpNatural = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\StandardizedData\\Tourism_zone.shp"
inpSurfaceWater = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\ProcessedData\\Surface_water.shp"
inpRivers = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\StandardizedData\\Rivers.shp"
inpGroundWater = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\StandardizedData\\grWat_poll.shp"

# SOCIAL criteria
inpLULC = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\ProcessedData\\lu_lc_build.tif"
inpNoisePoll = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\StandardizedData\\LU_res_dissol_1.shp"
inpAirPoll = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\StandardizedData\\LU_res_dissol_1.shp"
inpVillageExp = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\StandardizedData\\Village_expansion.shp"

#-------------------------------------------------

# Set files that are output from model

outFinal = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\FinalResultTlokweng\\"
outFinalWS = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\FinalResultTlokwengWS\\"
outFinalWO = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\FinalResultTlokwengWO\\"
outFinalCostDistance = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\FinalResultTlokwengCD\\"
outFinalCostPath = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\FinalResultTlokwengCP\\"
outFinalPolyline= "E:\\Milan_GIS\\MCD_Baza\\ModelData\\FinalResultTlokwengPolyline\\"
outFinalPolylineGeo= "E:\\Milan_GIS\\MCD_Baza\\ModelData\\FinalResultTlokwengPolyline\\RoadBypassAlignments.gdb\\"
outFinalNumCells= "E:\\Milan_GIS\\MCD_Baza\\ModelData\\FinalResultTlokwengNumCells\\"
outFinalNumMask= "E:\\Milan_GIS\\MCD_Baza\\ModelData\\FinalResultTlokwengMask\\"
outFinalTabels= "E:\\Milan_GIS\\MCD_Baza\\ModelData\\FinalResultTlokwengFinal\\"

# Files overwrite
arcpy.env.overwriteOutput = True

#-------------------------------------------------
# Check out the ArcGIS Spatial Analyst extension license
```

```
arcpy.CheckOutExtension("Spatial")

# Set extent variables
extFeatureClass = "E:\\Milan_GIS\\MCD_Baza\\Tlokweng_MCD.gdb\\Tlokweng_boundary"
desc = arcpy.Describe (extFeatureClass)
extent = desc.Extent
xMin = extent.XMin
xMax = extent.XMax
yMin = extent.YMin
yMax = extent.YMax

# Set extent for the feature classes
arcpy.env.extent = "MAXOF"
arcpy.env.extent = arcpy.Extent (xMin, yMin, xMax, yMax)
arcpy.env.cellSize = "MINOF"

# Set < extract by mask > feature classes
extMask = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\StandardizedData\\Tlokweng_boundary.shp"

# Set cell size (this comes from DEM raster dataset)
cellSize = 5

try:
    #------------
    # 1
    # Criteria SLOPE
    # Reclassify SLOPE
    outRecSlope = outFinal + "RecSlopeEcon.tif"
    RemapRangeSlope =  arcpy.sa.RemapRange([[0, 3, 1], [3, 5, 2], [5, 8, 3],[8, 12, 4], [12, 100000, 5]])
    rec_Slope = arcpy.sa.Reclassify (inpSlope, "VALUE", RemapRangeSlope, "NODATA")
    rec_Slope.save (outRecSlope)
    print "Criterion 1 - SLOPE is reclassified successfully !!!"
    print " "

    #------------
    # 2
    # Criteria ROADS
    # Polygon to Raster
    valFieldRoads = "Category"
    outRasterRoads = outFinal + "PolToRast_roads.tif"
    assignmentTypeRoads = "CELL_CENTER"
    priorityFieldRoads = "NONE"
    # Execute PolygonToRaster
    arcpy.PolygonToRaster_conversion(inpRoads, valFieldRoads, outRasterRoads, assignmentTypeRoads, priorityFieldRoads, cellSize)
    print "PolygonToRaster for ROADS is done successfully !!!"

    # Reclassify  ROADS
    outRecRoads = outFinal + "RecRoadsEcon.tif"
    RemapValueRoads = arcpy.sa.RemapValue([["Primary", 5], ["Secondary", 4], ["Teritary", 3], ["Tracks", 1], ["Access",2],["NODATA",1]])
    rec_Roads = arcpy.sa.Reclassify (outRasterRoads, "Category", RemapValueRoads, "")
    rec_Roads.save (outRecRoads)
    print "Criterion 2 - ROADS is reclassified successfully !!!"
    print " "

    #------------
    # 3
```

```
    # Criteria DRAINAGE
    # Polygon to Raster
    valFieldDrainage = "Strahler"
    outRasterDrainage = outFinal + "PolToRast_drainage.tif"
    assignmentTypeDrainage = "CELL_CENTER"
    priorityFieldDraiange = "NONE"
    # Execute PolygonToRaster
    arcpy.PolygonToRaster_conversion(inpDrainage, valFieldDrainage, outRasterDrainage, assignmentTypeDrainage, priorityFieldDraiange, cellSize)
    print "PolygonToRaster for DRAINAGE is done successfully !!!"

    # Reclassify  DRAINAGE
    outRecDraiange = outFinal + "RecDrainageEcon.tif"
    RemapValueDrainage = arcpy.sa.RemapValue([[1, 2], [2, 3], [3, 3], [4, 4], [5, 4], [6, 5],[7, 5], [8, 5], ["NODATA",1]])
    rec_Drainage = arcpy.sa.Reclassify (outRasterDrainage, "Value", RemapValueDrainage, "")
    rec_Drainage.save (outRecDraiange)
    print "Criterion 3 - DRAINAGE is reclassified successfully !!!"
    print " "

    #------------
    # 4
    # Criteria FLOODING
    # Euclidian Distance
    outEucDistFlooding = outFinal + "EucDist_floodzone.tif"
    EucDistFlooding = arcpy.sa.EucDistance(inpFlooding,"", cellSize)
    EucDistFlooding.save (outEucDistFlooding)
    print "Euclidian Distance for FLOODING is done successfully !!!"

    # Reclassify  FLOODING
    outRecFlooding = outFinal + "RecFloodingEcon.tif"
    RemapRangeFlooding = arcpy.sa.RemapRange([[1, 1], [2, 2], [3, 3],[4, 4],[5, 5], ["NODATA","NODATA"]])
    rec_Flooding = arcpy.sa.Reclassify (inpFlooding, "VALUE", RemapRangeFlooding, "NODATA")
    rec_Flooding.save (outRecFlooding)
    print "Criterion 4 - FLOODING is reclassified successfully !!!"
    print " "

    #------------
    # 5
    # Criteria GEOLOGY
    # Polygon to Raster
    valFieldGeology = "Category"
    outRasterGeology = outFinal + "PolToRast_geology.tif"
    assignmentTypeGeology = "CELL_CENTER"
    priorityFieldGeology = "NONE"
    # Execute PolygonToRaster
    arcpy.PolygonToRaster_conversion(inpGeology, valFieldGeology, outRasterGeology, assignmentTypeGeology, priorityFieldGeology, cellSize)
    print "PolygonToRaster for GEOLOGY is done successfully !!!"

    # Reclassify  GEOLOGY
    outRecGeology = outFinal + "RecGeologyEcon.tif"
    RemapValueGeology = arcpy.sa.RemapValue([[1, 1], [2, 4], [3, 3], [4, 2], [5, 4], ["NODATA",0]])
    rec_Geology = arcpy.sa.Reclassify (outRasterGeology, "VALUE", RemapValueGeology, "")
    rec_Geology.save (outRecGeology)
```

```
    print "Criterion 5 - GEOLOGY is reclassified successfully !!!"
    print " "

    #------------
    # 6
    # Criteria SOIL
    # Polygon to Raster
    valFieldSoil= "Sifra1"
    outRasterSoil = outFinal + "PolToRast_soil.tif"
    assignmentTypeSoil= "CELL_CENTER"
    priorityFieldSoil = "NONE"
    # Execute PolygonToRaster
    arcpy.PolygonToRaster_conversion(inpSoil, valFieldSoil, outRasterSoil, assignmentTypeSoil, priorityFieldSoil, cellSize)
    print "PolygonToRaster for SOIL is done successfully !!!"

    # Reclassify  SOIL
    outRecSoil = outFinal + "RecSoilEcon.tif"
    RemapValueSoil = arcpy.sa.RemapValue([["A1-A4b-A30a", 2], ["A4b-A30a", 4], ["A9", 4], ["A9-A11", 4], ["B3a", 4], ["G10c", 1], ["G1a-G1c", 5], ["G2d-G1a", 3],["R", 4],["NODATA",0]])
    rec_Soil = arcpy.sa.Reclassify (outRasterSoil, "Sifra1", RemapValueSoil, "")
    rec_Soil.save (outRecSoil)
    print "Criterion 6 - SOIL is reclassified successfully !!!"
    print " "

   #------------
    # 7
    # Criteria NATURAL_AREAS
    # Euclidian Distance
    outEucDistNaturalAreas = outFinal + "EucDist_natural.tif"
    EucDistNatural = arcpy.sa.EucDistance(inpNatural,"", cellSize)
    EucDistNatural.save (outEucDistNaturalAreas)
    print "Euclidian Distance for NATURAL_AREAS is done successfully !!!"

    # Reclassify  NATURAL_AREAS
    outRecNatural = outFinal + "RecNaturalEnv.tif"
    RemapRangeNatural = arcpy.sa.RemapRange([[0, 100, 5], [100, 200, 4], [200, 300, 3],[300, 500, 2],[500, 100000, 1]])
    rec_Natural = arcpy.sa.Reclassify (outEucDistNaturalAreas, "VALUE", RemapRangeNatural, "NODATA")
    rec_Natural.save (outRecNatural)
    print "Criterion 7 - NATURAL_AREAS is reclassified successfully !!!"
    print " "

    #------------
    # 8
    # Criteria SURFACE_WATER
    # Euclidian Distance
    outEucDistSurfaceWater = outFinal + "EucDist_SurWater.tif"
    cellSize = 5
    EucDistSurWater = arcpy.sa.EucDistance(inpSurfaceWater,"", cellSize)
    EucDistSurWater.save (outEucDistSurfaceWater)
    print "Euclidian Distance for SURFACE_WATER is done successfully !!!"

    # Reclassify  SURFACE_WATER
    outRecSurfWat = outFinal + "RecSurfWatEnv.tif"
    RemapRangeSurfWat = arcpy.sa.RemapRange([[0, 100, 5], [100, 200, 4], [200, 350, 3],[350, 500, 2],[500, 100000, 1]])
```

```
    rec_SurfWat = arcpy.sa.Reclassify (outEucDistSurfaceWater, "VALUE", RemapRangeSurfWat, "NODATA")
    rec_SurfWat.save (outRecSurfWat)
    print "Criterion 8 - SURFACE_WATER is reclassified successfully !!!"
    print " "

    #------------
    # 9
    # Criteria RIVERS
    # Euclidian Distance
    outEucDistRivers = outFinal + "EucDist_Rivers.tif"
    cellSize = 5
    EucDistRivers = arcpy.sa.EucDistance(inpRivers,"", cellSize)
    EucDistRivers.save (outEucDistRivers)
    print "Euclidian Distance for RIVERS is done successfully !!!"

    # Reclassify  RIVERS
    outRecRivers = outFinal + "RecRiversEnv.tif"
    RemapRangeRivers = arcpy.sa.RemapRange([[0, 100, 5], [100, 200, 4], [200, 350, 3],[350, 500, 2],[500, 100000, 1]])
    rec_Rivers = arcpy.sa.Reclassify (outEucDistRivers, "VALUE", RemapRangeRivers, "NODATA")
    rec_Rivers.save (outRecRivers)
    print "Criterion 9 - RIVERS is reclassified successfully !!!"
    print " "

    #------------
    # 10
    # Criteria GROUND_WATER
    # Euclidian Distance
    outEucDistGrndWat = outFinal + "EucDist_GrndWat.tif"
    EucDistGrndWat = arcpy.sa.EucDistance(inpGroundWater,"", cellSize)
    EucDistGrndWat.save (outEucDistGrndWat)
    print "Euclidian Distance for GROUND_WATER is done successfully !!!"

    # Reclassify  GROUND_WATER
    outRecGrndWat = outFinal + "RecGrndWatEnv.tif"
    RemapRangeGrndWat = arcpy.sa.RemapRange([[0, 150, 5], [150, 250, 4], [250, 350, 3],[350, 500, 2],[500, 100000, 1]])
    rec_GrndWat = arcpy.sa.Reclassify (outEucDistGrndWat, "VALUE", RemapRangeGrndWat, "NODATA")
    rec_GrndWat.save (outRecGrndWat)
    print "Criterion 10 - GROUND_WATER is reclassified successfully !!!"
    print " "

    #------------
    # 11
    # Criteria LC_LU
    # Reclassify LC_LU
    outRecLCLU = outFinal + "RecLCLUSocio.tif"
    RemapValueLCLU =  arcpy.sa.RemapValue([["No_Data", 2], ["SparseForest", 4], ["Woodland", 5],["OpenGrassland", 1], ["ClosedShrubland", 2], ["OpenShrubland", 2],["WaterBody", 5], ["Settlement", 5], ["Buildings", 5], ["LI", 2],["GI", 2], ["MXD-G", 5], ["C-3", 4], ["CIV", 4], ["R-1", 5], ["RSU", 5],["R", 5], ["MXD-C", 5], ["OS", 2],["R-2", 5], ["C-1", 5], ["iA-1", 5], ["Woodlands", 5], ["RU", 5], ["eA-2", 5], ["CBD", 5], ["'iA-1", 5], ["NODATA", "NODATA"]])
    rec_LCLU = arcpy.sa.Reclassify (inpLULC, "LULC", RemapValueLCLU, "NODATA")
    rec_LCLU.save (outRecLCLU)
    #------------
    print "Criterion 11 - LC-LU is reclassified successfully !!!"
```

```
    print " "

    #------------
    # 12
    # Criteria NOISE_POLLUTION
    # Euclidian Distance
    outEucDistNoise = outFinal + "EucDist_Noise.tif"
    EucDistNoise = arcpy.sa.EucDistance(inpNoisePoll,"", cellSize)
    EucDistNoise.save (outEucDistNoise)
    print "Euclidian Distance for NOISE_POLLUTION is done successfully !!!"

    # Reclassify  NOISE_POLLUTION
    outRecNoise = outFinal + "RecNoiseSocio.tif"
    RemapRangeNoise = arcpy.sa.RemapRange([[0, 25, 5], [25, 50, 4], [50, 125, 3],[125, 250, 2],[250, 100000, 1]])
    rec_Noise = arcpy.sa.Reclassify (outEucDistNoise, "VALUE", RemapRangeNoise, "NO-DATA")
    rec_Noise.save (outRecNoise)
    print "Criterion 12 - NOISE_POLLUTION is reclassified successfully !!!"
    print " "

    #------------
    # 13
    # Criteria AIR_POLLUTION
    # Euclidian Distance
    outEucDistAir = outFinal + "EucDist_Air.tif"
    EucDistAir = arcpy.sa.EucDistance(inpAirPoll,"", cellSize)
    EucDistAir.save (outEucDistAir)
    print "Euclidian Distance for AIR_POLLUTION is done successfully !!!"

    # Reclassify  AIR_POLLUTION
    outRecAir = outFinal + "RecAirSocio.tif"
    RemapRangeAir = arcpy.sa.RemapRange([[0, 100, 5], [100, 200, 4], [200, 300, 3],[300, 500, 2],[500, 100000, 1]])
    rec_Air = arcpy.sa.Reclassify (outEucDistAir, "VALUE", RemapRangeAir, "NODATA")
    rec_Air.save (outRecAir)
    print "Criterion 13 - AIR_POLLUTION is reclassified successfully !!!"
    print " "

except:
    print arcpy.GetMessages ()
    print "ERRORR!!!"


# ------------------------------------------------
# Criteria weights defintion

#Criteria weights for thema - Economy
baseSlope = 0.29
baseRoads = 0.11
baseDrainage = 0.16
baseFlooding = 0.07
baseGeology = 0.21
baseSoil = 0.16

#Criteria weights for thema - Enviro
baseNatural = 0.29
baseSurWater = 0.41
baseRivers = 0.19
baseGrdWater = 0.11

```

```
#Criteria weights for thema - Socio
baseNoise = 0.12
baseAir = 0.18
baseLCLU = 0.70

# ------------------------------------------------
# Hold values

# thema economy
themaEconomicNames = [outRecSlope, outRecRoads, outRecDraiange, outRecFlooding, outRecGeology, outRecSoil]
themaEconomicWeights = [baseSlope, baseRoads, baseDrainage, baseFlooding, baseGeology, baseSoil]
themaEconomicOut = ["Slope", "Roads", "Drain", "Flood", "Geol", "Soil"]

# thema enviro
themaEnviroNames = [outRecNatural, outRecSurfWat, outRecRivers ,outRecGrndWat]
themaEnviroWeights = [baseNatural, baseSurWater, baseRivers, baseGrdWater]
themaEnviroOut = ["Natr", "SurWat", "Rivr", "GrdWat"]

# thema socio
themaSocioNames = [outRecNoise, outRecAir, outRecLCLU]
themaSocioWeights = [baseNoise, baseAir, baseLCLU]
themaSocioOut = ["Noise", "Air", "LCLU"]

# theams combined
allThemasNames = [themaEconomicNames,themaEnviroNames,themaSocioNames ]
allThemasWeights = [themaEconomicWeights, themaEnviroWeights, themaSocioWeights]
allThemasOut = [themaEconomicOut, themaEnviroOut, themaSocioOut]


# ------------------------------------------------
# WEIGHTED SUM FOR ECONOMICAL CRITERIA
dictEcon = dict(zip(themaEconomicNames, themaEconomicWeights))
print dictEcon
wsTableEcon = []
dictEconKeys = dictEcon.keys ()
for s in dictEconKeys:
    dictEconValues = dictEcon[s]
    wsTableEcon.append ([s,"VALUE", dictEconValues])
print wsTableEcon
WSumTableObjEcon = WSTable(wsTableEcon)
outWeightedSumEcon = WeightedSum (WSumTableObjEcon)
outWeightedSumEcon.save (outFinal + "EconBase_WS")

# RECLASSIFY ECONOMY WEIGHTED SUM
outRecEcn = outFinal + "RecEconBase.tif"
RemapRangeEcon = arcpy.sa.RemapRange([[0, 1, 1], [1, 2, 2], [2, 3, 3],[3, 4, 4],[4, 5, 5]])
rec_econ = arcpy.sa.Reclassify (outWeightedSumEcon, "VALUE", RemapRangeEcon, "NODATA")
rec_econ.save (outRecEcn)
print "RECLASSIFACTION OF ECONOMY BASE is done successfully !!!"
print " "

# ------------------------------------------------
# WEIGHTED SUM FOR ENVIRONMENTAL CRITERIA
dictEnv = dict(zip(themaEnviroNames, themaEnviroWeights))
print dictEnv
wsTableEnv = []
```

```
dictEnvKeys = dictEnv.keys ()
for s in dictEnvKeys:
    dictEnvValues = dictEnv[s]
    wsTableEnv.append ([s,"VALUE", dictEnvValues])
print wsTableEnv
WSumTableObjEnv = WSTable(wsTableEnv)
outWeightedSumEnv = WeightedSum (WSumTableObjEnv)
outWeightedSumEnv.save (outFinal + "EnvBase_WS")

# RECLASSIFY ENVIRONMENTAL WEIGHTED SUM
outRecEnv = outFinal + "RecEnvBase.tif"
RemapRangeEnv = arcpy.sa.RemapRange([[0, 1, 1], [1, 2, 2], [2, 3, 3],[3, 4, 4],[4, 5, 5]])
rec_env = arcpy.sa.Reclassify (outWeightedSumEnv, "VALUE", RemapRangeEnv, "NODATA")
rec_env.save (outRecEnv)
print "RECLASSIFACTION OF ENVIRO BASE is done successfully !!!"
print " "
# --------------------------------------------------------

# WEIGHTED SUM FOR SOCIAL CRITERIA
dictSocio = dict(zip(themaSocioNames, themaSocioWeights))
print dictSocio
wsTableSocio = []
dictSocioKeys = dictSocio.keys ()
for s in dictSocioKeys:
    dictSocioValues = dictSocio[s]
    wsTableSocio.append ([s,"VALUE", dictSocioValues])
print wsTableSocio
WSumTableObjSocio = WSTable(wsTableSocio)
outWeightedSumSocio = WeightedSum (WSumTableObjSocio)
outWeightedSumSocio.save (outFinal + "SocioBase_WS")

# RECLASSIFY ENVIRONMENTAL WEIGHTED SUM
outRecSocio = outFinal + "RecSocioBase.tif"
RemapRangeSocio = arcpy.sa.RemapRange([[0, 1, 1], [1, 2, 2], [2, 3, 3],[3, 4, 4],[4, 5, 5]])
rec_socio = arcpy.sa.Reclassify (outWeightedSumSocio, "VALUE", RemapRangeSocio, "NODATA")
rec_socio.save (outRecSocio)
print "RECLASSIFACTION OF SOCIO BASE is done successfully !!!"
print " "

# --------------------------------------------------------
# Universal remap for Weighted Overlay
remapWO = RemapValue([[1,1],[2,2],[3,3],[4,4],[5,5],["NODATA","NODATA"]])

# --------------------------------------------------------
# Do itteration over themes (total 3 themes, loop can be set up as a variable)

for sLoop in range (0,3):

    procent = 0.01 # 1% defulat change in procent weight

    crit = 0
    critAdj = 0
    critRemTot = []
    restList = []
    product = []
    adjs = []
    names = []
    dictNames = {}
```

```

    print ("STARTED" + str(sLoop))
    print " "

    #crit_index = len(themaEconomicWeights)-1
    #print("list length is " + str(len(themaEconomicWeights)))

    for i, crit in enumerate(allThemasWeights[sLoop]): # do iteration over every criterion....

        print(allThemasNames[sLoop][i])

        critRemTot = [critWeight for k, critWeight in enumerate (allThemasWeights[sLoop]) if k != i]
        print critRemTot
        restList = [name for n, name in enumerate (allThemasNames[sLoop]) if n != i]
        print restList
        product = [s for z, s in enumerate(allThemasWeights[sLoop]) if z != i]
        allCritWeigh = sum(product)

        # check if additive constraion - sum of the criteria weights is 1,000
        print "Sum of the weights, not including the main criteria is: " + str (allCritWeigh)
        print " "

        print zip(restList, critRemTot)
        finWeight = [x/allCritWeigh for x in critRemTot]
        print finWeight
        print " "

        listCellsTot = []
        countCells = ""
        checkList = [1, 2, 3, 4, 5]

        # Input for comparision among the cells
        listCellsTotRast = []
        checkRasterList = [11, 12, 13, 14, 15, 21, 22, 23, 24, 25, 31, 32, 33, 34, 35, 41, 42, 43, 44, 45, 51, 52, 53, 54, 55]

        for j in range(-20 ,21, 1): # Loop over criterion weights change

            print("procent: %s" % j)
            critInc =crit * procent * j
            critAdj = round ((crit + critInc),6)
            print critAdj

            print " "
            adjs = [ round ((1 - critAdj) * critInProd, 6)  for k, (critInProd) in enumerate(finWeight)]
            names = [name for k, name in enumerate (allThemasNames[sLoop]) if k != i]
            print zip(names, adjs)
            print " "
            adjs.append (critAdj)
            names.append (allThemasNames[sLoop] [i])
            print " The total sum of the weights is: " + str (sum(adjs))
            print zip(names, adjs)

            dictNames = dict(zip(names, adjs))
            print dictNames
            print " "
```

```

            newList = []
            sKeys = dictionary.keys()
            for s in sKeys:
                sValues = dictionary [s]
                newList.append ([s,"VALUE", sValues])
            print newList
            print "New list for " + (("procent: %s" % j))

            # Create the WSTable object
            WSumTableObj = WSTable (newList)
            outWeightedSum = WeightedSum (WSumTableObj)
            currItt =   allThemasOut[sLoop][i]
            outWeightedSum.save (outFinalWS + currItt + "_" + str(j))

            # DO RECLASIFFY for input in Weighted Overlay Table
            outRec = outFinalWO + "RecSLoop" + str(sLoop)+ str(j) #+  ".tif" # can include this to seperate the rec files but not necessary ------> str(j)+ str(sLoop) +
            RemapRangeWO = arcpy.sa.RemapRange([[0, 1, 1], [1, 2, 2], [2, 3, 3],[3, 4, 4],[4, 5, 5]])
            rec_baseSLoop = arcpy.sa.Reclassify (outWeightedSum, "VALUE", RemapRangeWO, "NODATA")
            rec_baseSLoop.save (outRec)
            print "RECLASSIFACTION OF BASE - sLopp is done successfully !!!"
            print " "

            # Check each theme in the list according to the used loops, and reapeat all the steps accordingly
            if sLoop == 0:

                # ECONOMY thema is the first element in defined python list, thus sLoop = 0
                # Do Weighted Overlay (first raster within WOTable is always under loop), Economy
                myWOTable = WOTable([[rec_baseSLoop, 50, "VALUE", remapWO], [rec_env, 25, "VALUE", remapWO], [rec_socio, 25, "VALUE", remapWO]], [1, 5, 1])
                # Execute Weighted Overlay
                outWeightedOverlay = WeightedOverlay(myWOTable)
                # Save the output
                outWeightedOverlay.save(outFinalWO + currItt + "_" + str(j))
                print "Raster datasets for Weighted Overlay was created "
                print " "
                # Do the extract  by mask
                outExtractByMask = ExtractByMask (outWeightedOverlay,extMask)
                outExtractByMask.save (outFinalNumMask + currItt + str(j))

            elif sLoop == 1:

                # ENVIRONMETANL thema is the second element in defined python list, thus sLoop = 1
                # Do Weighted Overlay (first raster within WOTable is always under loop), Economy
                myWOTable = WOTable([[rec_baseSLoop, 50, "VALUE", remapWO], [rec_econ, 25, "VALUE", remapWO], [rec_socio, 25, "VALUE", remapWO]], [1, 5, 1])
                # Execute Weighted Overlay
                outWeightedOverlay = WeightedOverlay(myWOTable)
                # Save the output
                outWeightedOverlay.save(outFinalWO + currItt + "_" + str(j))
                print "Raster datasets for Weighted Overlay was created "
```

```
                print " "
                # Do the extract  by mask
                outExtractByMask = ExtractByMask (outWeightedOverlay,extMask)
                outExtractByMask.save (outFinalNumMask + currItt + str(j))

            elif sLoop == 2:

                # SOCIALthema is the second element in defined python list, thus sLoop = 2
                # Do Weighted Overlay (first raster within WOTable is always under loop), Economy
                myWOTable = WOTable([[rec_baseSLoop, 50, "VALUE", remapWO], [rec_econ, 25, "VALUE", remapWO], [rec_env, 25, "VALUE", remapWO]], [1, 5, 1])
                # Execute Weighted Overlay
                outWeightedOverlay = WeightedOverlay(myWOTable)
                # Save the output
                outWeightedOverlay.save(outFinalWO + currItt + "_" + str(j))
                print "Raster datasets for Weighted Overlay was created "
                print " "
                # Do the extract  by mask
                outExtractByMask = ExtractByMask (outWeightedOverlay,extMask)
                outExtractByMask.save (outFinalNumMask + currItt + str(j))

            # Do Cost Distance raster
            inSourceDataStart = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\ProcessedData\\Points\\Start.shp"
            inCostDistRast = outExtractByMask
            outBkLinkRaster = (outFinalCostDistance + currItt + "bl_" + str(j))
            # Execute CostDistance
            outCostDistance = CostDistance(inSourceDataStart, inCostDistRast, "", outBkLinkRaster)
            # Save the output
            outCostDistance.save(outFinalCostDistance + currItt + "cd_" +  str(j))
            print ("Raster datasets for Cost Distance was created " + currItt + "cd_" + str(j))
            print " "

            # Do Cost Path raster
            inSourceDataEnd = "E:\\Milan_GIS\\MCD_Baza\\ModelData\\ProcessedData\\Points\\End.shp"
            inCostPathRas = outCostDistance
            outCostBLinkRaster = outBkLinkRaster
            method = "EACH_CELL"
            # Execute Cost Path
            outCostPath = CostPath(inSourceDataEnd, inCostPathRas , outCostBLinkRaster, method, "")
            # Save the output
            outCostPath.save(outFinalCostPath +  currItt + "cp_" +  str(j))
            print ("Raster datasets for Cost Path was created " + "cp_" + str(j))
            print " "

            # Convert raster path to polyine, not necessary but have it done here....
            inRasterToPolyline =  outCostPath
            outPolyline = (outFinalPolyline +  currItt + "cp_" +  str(j))
            backgrVal = "ZERO"
            field = "VALUE"
            # Execute RasterToPolygon
            arcpy.RasterToPolyline_conversion(inRasterToPolyline, outPolyline, backgrVal, "", "SIMPLIFY", field)
```

```
            # Save polyline to geodatabase
            arcpy.FeatureClassToGeodatabase_conversion (outPolyline + ".shp", outFinalPolylineGeo)
            print ("Raster datasets for Cost Path was converted to polyline shapefile " +  currItt + "cp_"+ str(j))
            print " "

            #  IF-statements can be re-structured, but keep it for now !!!
            if sLoop == 0:

                # Perfrom raster calculator to calculate the number of cells
                #numCells = (outCostPath & outWeightedOverlay) * outWeightedOverlay
                #numCells.save (outFinalNumCells+  currItt + "cp_" + str(sLoop)+ str(j))

                # start with exporting data
                countCells = str(j)
                rows = arcpy.SearchCursor (outExtractByMask)
                nullList = [countCells, 0, 0, 0, 0, 0]
                for row in rows:
                    for elem in checkList:
                        if row.Value == elem:
                            nullList [elem] = row.Count
                listCellsTot.append (nullList)
            elif sLoop == 1:

                # Perfrom raster calculator to calculate the number of cells
                #numCells = (outCostPath & outWeightedOverlay) * outWeightedOverlay
                #numCells.save (outFinalNumCells+  currItt + "cp_" + str(sLoop)+ str(j))

                # start with exporting data
                countCells = str(j)
                rows = arcpy.SearchCursor (outExtractByMask)
                nullList = [countCells, 0, 0, 0, 0, 0]
                for row in rows:
                    for elem in checkList:
                        if row.Value == elem:
                            nullList [elem] = row.Count
                listCellsTot.append (nullList)
            elif sLoop == 2:

                # Perfrom raster calculator to calculate the number of cells
                #numCells = (outCostPath & outWeightedOverlay) * outWeightedOverlay
                #numCells.save (outFinalNumCells+  currItt + "cp_" + str(sLoop)+ str(j))

                # start with exporting data
                countCells = str(j)
                rows = arcpy.SearchCursor (outExtractByMask)
                nullList = [countCells, 0, 0, 0, 0, 0]
                for row in rows:
                    for elem in checkList:
                        if row.Value == elem:
                            nullList [elem] = row.Count
                listCellsTot.append (nullList)

        # create list for each criteria
        listCellsTot.insert (0, ["Iteration", "Cells_1", "Cells_2", "Cells_3", "Cells_4", "Cells_5"])
        print listCellsTot
```

```
        with open (outFinalTabels + allThemasOut[sLoop][i] + ".csv", "wb") as fp:
            a = csv.writer (fp, delimiter=",")
            a.writerows (listCellsTot)


        # Loop over raster datasets, create new .csv files to insert calculating values for cells chanching...
        # 1 --> 1    1 --> 2  1 --> 3  1 --> 4  1 --> 5 ;    2 --> 1  2 --> 2  2 --> 3  2 --> 4  2 --> 5 ;
        # 3 --> 1    3 --> 2  3 --> 3  3 --> 4  3 --> 5   ;  4 --> 1  4 --> 2  4 --> 3  4 --> 4  4 --> 5 ;
        # 5 --> 1    5 --> 2  5 --> 3  5 --> 4  5 --> 5
        env.workspace = outFinalNumMask
        rasterList = arcpy.ListRasters (currItt + "*","")
        print rasterList
        print " "
        print " "
        rasterBase = Raster (outFinalNumMask + currItt + "0")

        for num in range (-20 , 21, 1): # the same range as for criterion weight
            rasterInp =  Raster (outFinalNumMask + currItt + str(num))
            desc = arcpy.Describe (rasterInp)
            print desc.dataType
            print desc.name

            # Perform raster calculator between BASE and input raster - rasterCal
            rasterCalOut = outFinalNumMask + currItt + "rast" + str(num)

            #rastTemp = Con(rasterInp > rasterBase, 1, 2)
            #rastTemp = Con(rasterBase == 1, (Con(rasterInp == 1, 11, Con(rasterInp == 2, 12 , Con(rasterInp == 3, 13, Con(rasterInp == 4, 14, Con(rasterInp == 5, 15)))))))
            #rastTemp = Con(rasterBase == 1 , 100, 200)
            rastTemp =  Con(rasterBase == 1, (Con(rasterInp == 1, 11, Con(rasterInp == 2, 12 , Con(rasterInp == 3, 13, Con(rasterInp == 4, 14, Con(rasterInp == 5, 15)))))), \
            Con(rasterBase == 2, (Con(rasterInp == 1, 21, Con(rasterInp == 2, 22 , Con(rasterInp == 3, 23, Con(rasterInp == 4, 24, Con(rasterInp == 5, 25)))))), \
            Con(rasterBase == 3, (Con(rasterInp == 1, 31, Con(rasterInp == 2,32 , Con(rasterInp == 3, 33, Con(rasterInp == 4, 34, Con(rasterInp == 5, 35)))))), \
            Con(rasterBase == 4, (Con(rasterInp == 1, 41, Con(rasterInp == 2, 42 , Con(rasterInp == 3, 43, Con(rasterInp == 4, 44, Con(rasterInp == 5, 45)))))), \
            Con(rasterBase == 5, (Con(rasterInp == 1, 51, Con(rasterInp == 2, 52 , Con(rasterInp == 3,53, Con(rasterInp == 4, 54, Con(rasterInp == 5, 55))))))))))

            #rastTemp =  Con(rasterBase == 1, (Con(rasterInp == 1, 11, Con(rasterInp == 2, 12 , Con(rasterInp == 3, 13, Con(rasterInp == 4, 14, Con(rasterInp == 5, 15)))))), Con(rasterBase == 2, (Con(rasterInp == 1, 21, Con(rasterInp == 2, 22 , Con(rasterInp == 3, 23, Con(rasterInp == 4, 24, Con(rasterInp == 5, 25)))))), Con(rasterBase == 3, (Con(rasterInp == 1, 31, Con(rasterInp == 2,32 , Con(rasterInp == 3, 33, Con(rasterInp == 4, 34, Con(rasterInp == 5, 35)))))), Con(rasterBase == 4, (Con(rasterInp == 1, 41, Con(rasterInp == 2, 42 , Con(rasterInp == 3, 43, Con(rasterInp == 4, 44, Con(rasterInp == 5, 45)))))), Con(rasterBase == 5, (Con(rasterInp == 1, 51, Con(rasterInp == 2, 52 , Con(rasterInp == 3,53, Con(rasterInp == 4, 54, Con(rasterInp == 5, 55))))))))))
```

```
            print type(rastTemp)

            rastTemp.save (rasterCalOut)
            desc = arcpy.Describe (rasterCalOut)
            print desc.dataType
            print desc.name

            countCellsRast = str(num)
            rows = arcpy.SearchCursor (rasterCalOut)
            nullListRast = [countCellsRast, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
            for row in rows:
                for elem in checkRasterList:
                    if row.Value == elem:
                        s = checkRasterList.index (elem)
                        nullListRast [s+1] = row.Count
            listCellsTotRast.append (nullListRast)
        # create list for each criteria
        listCellsTotRast.insert (0, ["Iteration", "11", "12", "13", "14", "15" , "21", "22", "23", "24", "25", "31", "32", "33", "34", "35", "41", "42", "43", "44", "45", "51", "52", "53", "54", "55"])
        print listCellsTotRast

        with open (outFinalTabels + currItt + "Sensitivty" + ".csv", "wb") as fp:
            a = csv.writer (fp, delimiter=",")
            a.writerows (listCellsTotRast)

arcpy.CheckInExtension("Spatial")
```

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