GIS APPLICATION IN DESIGNING POTENTIAL ECOLOGICAL CORRIDORS

(Alora case study, Spain)

Njuguna, E.C.

February 2000

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Thesis submitted in partial fulfilment of the degree of Masters of Science in Geo-Information Systems for Rural Application at the Wageningen University (WU) and the International Institute for Aerospace Survey and Earth Sciences (ITC).
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For my wife, Jane Wambui
And our lovely kids
Njuguna, Wangari and Kingori

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And to all, remember that “Geography brings us together”.

ABSTRACT

Habitat fragmentation has been identified as one of the main cause of wildlife population decline and even extinction. To mitigate the problem, the development of migration corridor routes has been recommended for maintaining landscape connectivity thus preserving habitat for movement of species between the remaining fragments. The thesis proposes the use of biological habitat models in an interactive geographic information system (GIS) environment for a proper scientific corridor design. This will allow spatial analysis of the required information and presentation of results in a spatial manner rather than in a mathematical format only. A GIS process model is developed to assist in the task of delineating suitable habitat patches and the connecting corridors. This was achieved by integrating a wolf habitat suitability model function into a raster GIS, for creating suitability maps, and hence delineating suitable habitat patches. Means of assessing habitats at different scales using variable windows of analysis is described. GIS functions of distance and weighted distance are used to generate a network of potential corridor routes in areas made up of remnant forests separated by barriers like highways, agricultural, and settlement areas. The process model has been depicted with flowcharts showing, input data layers, the GIS procedure performed, and the out put data layer that may be used as input to another procedure. An attempt has been made to allow generation of “what if” scenarios by allowing the user to adjust some of the model variables for aiding the decision making process.

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1 INTRODUCTION

Human activities, such as large-scale agriculture, energy projects, construction, water resources, or agricultural projects driven by increasing resources consumption with increasing affluence and population numbers, considerably affect the natural environment (Fedra, 1994). The reduction of the natural habitats of many flora and fauna species, partial destruction of some ecosystems and fragmentation of natural landscapes are important negative results of degradation and devastation of the environment due to natural processes and human activities (Collinge, 1998, Forman 1995). The problem of renewing connections between separate protected areas, forest, marshes, etc. has arisen. Its solving would significantly improve conservation and free migrations of animals when settling and looking for food. The sustainability of populations and ecosystems in general will be increased. This concerns mammals first of all, who depend very much on the sustainability of their habitats, as well as improve migration of other animals (birds, reptiles, invertebrates' etc.) and spreading of plants (UNDP, 1993). Therefore, the establishment of ecological corridors is very important and it has to become one of the priorities of environment protection activity in such situations.

There are many continental, national, regional and local greenways programs currently being planned and implemented (Florida report, 1999). Some of the examples include:

1. The Florida state-wide greenways planning (USA)
2. American Wildlands Northern rocky reserve project (USA)
3. The Pan European Ecological Network ("EECONET") currently being planned by the European Centre for Nature Conservation to encompass all 18 countries within the European Union among many others
4. The ecological main structure (EMS), the Netherlands

Geographic Information system (GIS) tools have been applied in these projects in one way or another using different approaches. Therefore, there is need to develop a general GIS approach to facilitate a proper matching of corridor design requirements with the existing environment from the experience of such projects. This kind of approach could be used in any other areas where corridors for habitat connectivity are to be planned.

A corridor can be defined as a spatial feature of vegetation or land use type, which differs from the surrounding vegetation and connects at least two habitats that were connected in historical time (Saunders and Hobbs, 1991). In order to designate wildlife corridors, it is essential to think through the reason for designation i.e. the function of the corridor. Forman, (1995) identified four major functions, which includes:

1. habitat for certain species
2. conduit for species movement
3. filter or barrier separating habitats
4. sink or source of species for the surrounding matrix

There have been many debates on the values of corridors in facilitating the movement of species. Still, many scientists (Merriam, 1991; Harris and Scheck, 1991; Walker and Craighead, 1997) have argued for their retainment in maintaining connectivity of fragmented habitats. Their use will likely:

1. maintain continuity between sub-populations in a meta-population
2. allow previously unexploited habitat to become available
3. prevent and/or reverse local extinction
4. enable an individual species to access resource needed daily or periodic as in migrant species
5. promote the exchange of genes between sub-populations to raise the effective population size and decrease potential impacts of genetic drift and inbreeding depression

Hence, when spatial features of vegetation are designated as corridors they should foster the movement of species. Each species has particular requirements to be met, so before any strip can act as a corridor, there is need to establish these requirements for the resident species and if not for all, then for those species that are of critical conservation interest (Merriam, 1991).

A corridor can function at several scales. It is then essential to understand the regional settings involved. In some instances, patchwork reserves acting like corridors may already exist in the landscape with the corridors being designated to enhance these for the intended function. Whereas, in other instances we may be starting from scratch with our proposed corridors in an otherwise totally cleared landscape. Hence, the planning of landscape (in which corridors are part of) requires placing it in the spatial context of other landscapes in a region or even in a continent. This hierarchy of levels is identified so that the planning can be understood as part of a larger system and specific places can be seen as part of the whole region (Steiner, 1991). This necessitates biophysical inventory at different scales of details namely at regional, landscape and local scales preferably in some form of a GIS environment (Saunders and De Rebeira, 1991). The information in the inventory should include distribution and abundance of vegetation, geology, soils, topographic, climatic factors and fauna among many other. In the absence of detailed ecological knowledge for most plant and animal species and communities, some interpolation can be done based on sample data sets (McGregor, 1998). That is connectivity may be facilitated by selecting the potential location of corridors on the basis of their climate attributes together with location, elevation and topographic attributes which strongly influence climatic conditions of an area (Norton and Nix, 1991).

In Alora, the sustainability of existing land use activities is in question. Agriculture is highly dependent on unreliable rainwater and irrigation water for agriculture is in high competition with domestic, industrial and tourist demands of surrounding towns and cities like Malaga, on the Costa del Sol (Findings during Alora field work case study, May 1999). Nature conservation as one of the land use activities is gaining prominence among the stakeholders in the region. Thus, there is need to look at the conservation possibilities and means of management with the help of tools like GIS and Remote Sensing. The goal is to protect and manage an overall landscape that effectively protects biological diversity while supporting other compatible and productive land uses in a sustainable manner at the local scale.

Problem statement

Corridor research is inherently multi-disciplinary. Basic research in areas such as behaviour, genetics and ecology are sources of necessary data. Fields such as computer science, geography and mathematics provide the theoretical framework and tools needed to quantify ecological landscapes (Witteman and Gilpin, 1995). Ecosystem managers, conservation biologists in reserve design or land use policy makers may then apply the resulting information, models and analysis in decision making. In practice, the design of suitable habitats and corridors necessitates co-ordinating the likely conflict between natural conservation and regional economic development. Scientific design of habitats and corridors therefore becomes increasingly important rather than simply encircling and joining the areas where the target species is frequently observed (Wenjun et al., 1999). This will help to overcome the problem of excluding any suitable or potentially suitable habitats in the design of conservation areas and the connecting corridor zones. The tools and models used need to be dynamic in order to construct a range of different scenarios and should not be restricted to a single set of input or output. The interactions between landscape elements and animal species, which live in them, are spatial in nature. To ensure the results are used by planners and stake holders, they need to be presented in a spatial manner, that is visually rather than in a mathematical format only.

Reviewing the enumerated requirements and constrains on corridor design and detection, GIS may be the key tool to the corridor scientist for landscape representation, data storage, analysis and visualisation in the process of design and implementation (Witteman and Gilpin, 1995). A prerequisite for maintenance of biological diversity is the access to appropriate knowledge on the distribution and the relative abundance of the biota and the ecological processes affecting these patterns. The challenge for ecologists and managers is to assemble the information necessary, to enable the successful designation of corridors to enhance the movement function for species. Frequently however, this type of information may be exceedingly limited or non-existent. Increasingly, scientists and managers have turned to computers to optimise the formalisation, collection and analysis of the information in biological systems. Biological modelling and GIS are two complementary methodologies, which provide significantly increased opportunities for more detailed environmental resources inventory, and analysis and show considerable promise for extensive use in nature conservation (Norton and Nix, 1991).

1.1 Objectives

The main objective of this research is to formalise in a GIS environment the thinking steps of identifying potential ecological corridor locations to facilitate wildlife species movement. The approach will enhance corridor analysis by integrating habitat suitability analysis with GIS technology to identify suitable sites for corridors in the Alora region of southern Spain. The case study concerns wolf re-introduction in the region. A GIS process model will be developed with the following specific objectives:

1. Integration of GIS with habitat statistical models for spatial analysis and visualisation
2. Identification of suitable habitat patches for species re-introduction
3. Identification of suitable connecting corridors between the patches

4. Generation of different corridor scenarios to aid in decision making

To achieve the objectives of the research, the following research questions have to be answered:

1. What aspects need to be considered in corridor design?
2. What information (data) is required?
3. What are the required steps in designing an ecological corridor?
4. What are the main data processing and integration requirements and how can they be implemented in a GIS environment?

1.2 Study approach

The approach to this study is based on the assumption that successful habitat suitability evaluation and analysis can serve as the foundation for potential corridor design (Wenjuin et al., 1999; Miller et al., 1998; Swetnam et al., 1998). The most simple and widely used method for evaluation and land use planning is mapping. A map model is an alternative form of looking at reality. Hands made maps are predominantly static and expensive to redraw when object definitions (attributes) change. However, GIS have interactive ways of mapping in which storing, handling, analysing information and updating databases can be quick and cost-effective (De La Ville, 1997). The thesis proposes the application of a habitat suitability model function in a GIS environment. After mapping and identifying the suitable habitat patches, optimal connecting routes through the landscape matrix are delineated which could be designated as ecological corridors.

The habitat suitability function (HSF) converts the maps of various habitat characteristics into a single map of habitat suitability. The next step is to find habitat patches. This requires a recognition algorithm to find cluster or groups of contiguous cells of suitability values higher than or equal to a given threshold habitat value. The identified clusters are then the potential suitable habitat patches.

A common method applied in GIS is reclassification. This function uses the criteria of threshold values. In this case, threshold value is the minimum habitat suitability value as defined by the habitat function below which the habitat is not suitable for reproduction and/or survival, although individuals may disperse or migrate through habitat that has a suitability value lower than this threshold. Neighbourhood distance functions are used to identify contiguous cells that belong to the same patch (Akcakaya, 1996).

By following the above stated approach, a GIS processing model will be developed that allows users to perform the identified tasks interactively.

1.3 Thesis Outline

The thesis is divided into five chapters. In brief the next four chapters are:

Chapter two, Background aspects: The habitat evaluation, which is the basis of corridor design, is discussed with a review of the evaluation requirements, which include: Species requirements, landscape evaluation and their relationship through statistical regression function. The functions of GIS and Remote Sensing are discussed with their role as tools for environmental modelling.

Chapter three, Materials and Methods: This section focuses on the design of ecological corridors. The habitat model function is introduced along with the data requirements. The general steps in corridor design are defined. The GIS approach to corridor design is developed by defining the data capture methods and pre-processing, the application of the habitat model function in GIS and the delineation of potential suitable habitat patches and corridor routes using GIS mathematical functions.

Chapter four, Results and discussion: Presents the results including the process model developed and different corridor scenarios within the case study area of Alora.

Chapter five: Conclusion of the thesis is presented.

2 BACKGROUND ASPECTS

2.1 Introduction

Corridor design falls under the broad issue of land use planning. Their sustainability depends on long term sustainable land management policies, taking into consideration the needs for nature conservation and the needs of human development activities. Conservation measures include the protection of wildlife and their habitats, the maintenance of forest or wilderness areas, the control of air and water pollution, and the prudent use of farmland, mineral deposits, and energy supplies. The wildlife movement requirement is one of the most constrained, resulting in isolation of animal species hence population declines and even extinction. In patchy heterogeneous landscape, conservation objective can then be restated as preventing local patch extinction from accumulating into landscape, then regional and subcontinent extinction (Merriam, 1991). To mitigate the problem, the development of migration corridor routes has been recommended as one of the protection measures for maintaining landscape connectivity thus preserving habitat for movement of species between the remaining fragments. Width of the corridor, length, type of habitat, human activities, and location are considered the most important characteristics that affect corridor utility (Burbrink et al., 1998). The designation of an area as a wildlife corridor might be in conflict with other development plans, which are of interest to other stakeholders. Thus, apart from species ecological requirements being one of the main considerations in the design, the social economic aspect of the community and the surrounding landscape are important as well (Figure 1). GIS has the potential to assist in negotiating settlement of land use conflict, if it is used in a way that is interactive and perceptible to all involved (Hurni, 1997). Habitat requirements of a species include several factors. This are easily integrated using GIS. The GIS allows one to see the habitat patches as may be perceived by the animal species and their spatial arrangement in relation to other activities.

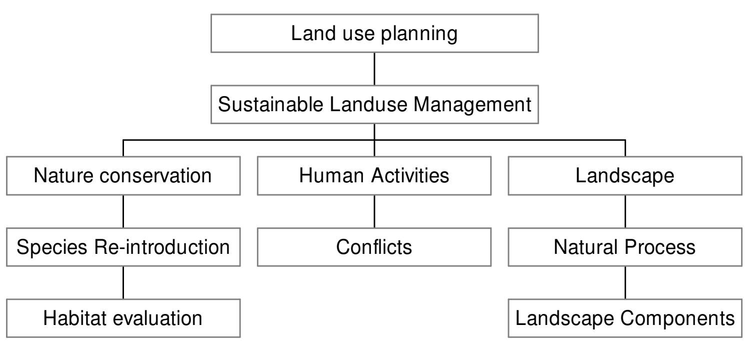

Figure 1. The broad Issues related to nature conservation activity of species re-introduction

2.2 Case Study: Re-introduction of wolf

The wolf is one of the animal species that has been exterminated in many parts of Spain and Europe in general (Delibes, 1990; De La Ville, 1997). In Andalucia, southern Spain, there are plans to reintroduce the wolf. Areas for protection or reintroduction should take into account that wolves are a highly mobile species. They tend to follow prey migration. Therefore recovery zones should consider wolf dispersal corridors and land use zoning (Mech, 1996). These factors are important since suitable areas with nearly the minimum size to ensure viable wolf populations are usually fragmented into smaller units. The suitable areas are usually surrounded by zones with strong human activities and human presence. Therefore, public acceptance and sentiments in designing wolf corridors and land use zoning is an important aspect. When setting boundaries for management zones, different levels of wolf protection can be applied, within public and private agricultural lands. This leads to an effective management plan to conserve the wolf and it's habitats (De La Ville, 1997).

One assumption when reintroducing animals to parts of their original range is that, conditions have improved well enough to guarantee a chance of survival. Habitat evaluation using models can be used in identifying and assessing the conditions of these areas. Spatially delineating suitable habitat for large carnivores within mixed, managed landscapes is beneficial in assessing recovery potentials and managing animals to minimise human conflict (Mladenoff et al., 1999). Habitat suitability models based on easily measurable variables, compatible with standard vegetation classification systems for which inventories are readily available, can increase model adaptability (De La Ville, 1997). This increases the possibilities for future development and application of the model.

2.3 Species habitat evaluation

2.3.1 Habitats

An animal's habitat is where it lives. Each species including humans has unique, fundamental needs for food, shelter, water and space and can live only where their specific combination of habitat requirements are available. The landscape characteristics, which are important for habitat evaluation, vary according to region and the specific wildlife species. The suitability is often determined by an evaluation of life requirements that is supplied by landscape features (Figure 2). The habitat can thus be described as the physical structure, vegetation composition, and physiognomy of an area, the characteristics of which determine its suitability for particular animal or plant species (GAP, 1996).

2.3.2 Evaluation

Habitat evaluation is complex especially for large areas and for mobile species that exploit resources from a variety of landscape features in different and distance locations (Garcia and Armbruster, 1997). Models used to describe the requirements of a particular species must fulfil the following:

1. define the resources to be supplied by a habitat
2. identify the landscape features that supply these resources
3. document the response of the animals to the supplied resources

In general within a geographic region, species respond differently to habitat changes because of different requirements and scales at which they interact with the environment. The difference in habitat requirements reflects fundamental differences in individual species life history requirements and population structure (Riitters et al., 1997).

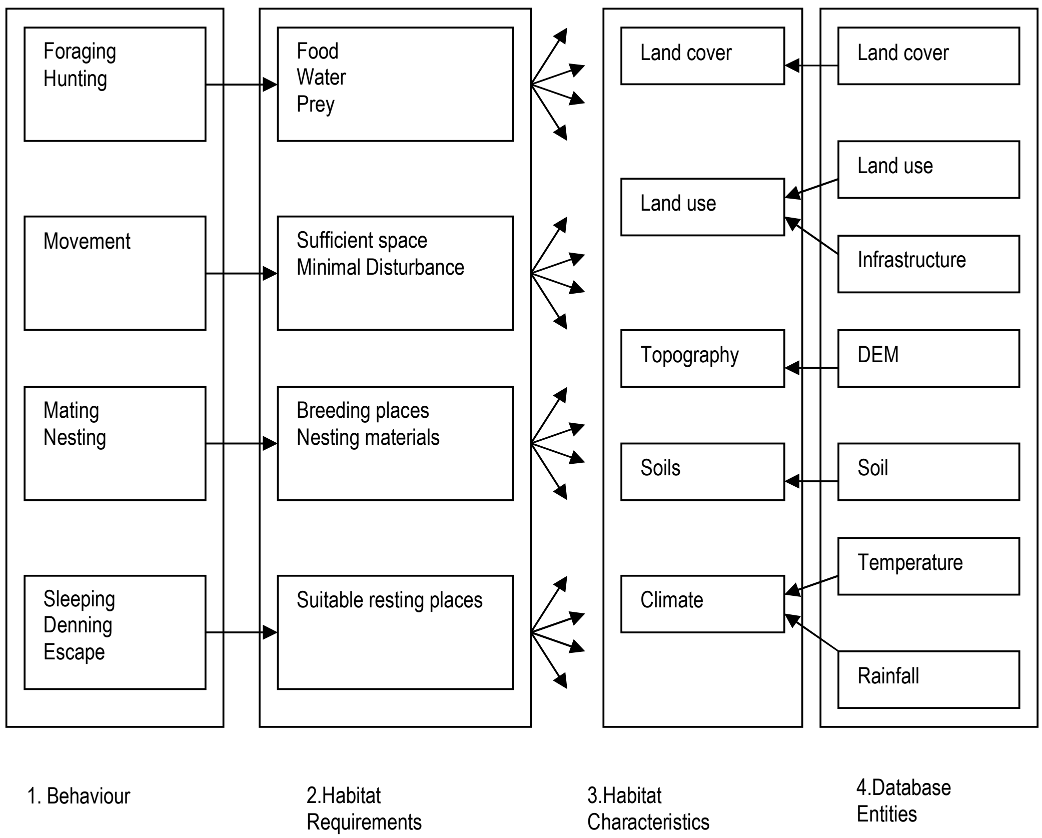

Figure 2. Relationship between animal requirements and landscape (Adapted from Tamis and Zelfde, 1998)

The following sections explore the three model considerations identified above in relation to the case study.

2.3.3 Wolf habitat

Many studies have been undertaken to study the factors affecting wolf distribution in the landscape (Alesandro and Alberto, 1998; Mladenoff et al., 1995 and 1999; De La Ville 1997; Harrison and Chapin, 1998). Three important factors identified in determining wolf habitat suitability include; Wild prey abundance, human presence and forest cover (Alesandro and Alberto, 1998).

In general terms, an example of wolf habitat / landscape relationship is given by the U.S. Fish & Wildlife Service (De La Ville, 1997) which suggests that the optimum habitat for wolves have to satisfy the requirements of:

1. A sufficient prey base
2. Suitable, secluded denning and meeting sites
3. Sufficient space with minimal exposure to humans (min 10,000 Km^2.), including wolf travel corridors
4. Maximum 10% of private land ownership
5. And absence, if possible, of livestock grazing

Wolf preys on wide variety of species (Mech, 1996). It is an umbrella species with a large area requirement, which, if given sufficient protected habitat area, will bring many other species under protection. The wolf is a habitat generalist; able to adapt to the most varied habitats (Mladenoff et al., 1999). However, in overpopulated regions, like in Europe, it needs undisturbed retreat areas to rest and breed (Delibes, 1990).

Habitat descriptors, selected for building a wolf model, include the physical parameters of weather (temperature and rainfall) and elevation (Table 1). The plant architecture is also a determining factor for the species presence or absence. Wolves are less vulnerable from human persecution in more complex plant architecture; e.g. wolf hunting from aircraft is less common in forests and woodlands than in grasslands (De La Ville, 1997). Other indices identified include land cover types and patch boundary complexity, landscape dominance and diversity. Therefore the physiognomy of the vegetation, represented as the coverage of herbaceous and woody elements, can be used as a measure of vegetation structure. Finally, human disturbances should be taken into account. These include road density, human population density, agricultural areas, and land ownership classes as indicators of human disturbance.

Table 1: Habitat descriptors for wolf model as identified in various studies.

Habitat Descriptors
Temperature patterns
Rainfall patterns
Topography (Elevation)
Human population (density)
Land cover: potential vegetation
Transport network (Road & Rail)
Protected or conservation areas
Cultural and key locations
Drainage network

The wolf habitat requirements and factors influencing it are many and varied. Hence, the factors selected for evaluation will depend on the particular habitat model applied, the availability of data, and the ease of measurement for the selected factors. In the Alora case study, the factors considered were mainly, physical characteristics of land cover, land use and human related factors of roads and human settlements.

2.3.4 Landscape studies.

In the previous section, the importance of landscape as a source of species requirements has already been mentioned. The importance of understanding and studying landscapes is illustrated when looking at an ecological phenomenon such as re-colonisation. Re-colonisation is enhanced by spatial patterns such as corridors, networks, stepping stones, and small patches (Forman, 1991). Landscape mosaics are described by the landscape components of patches, corridors, and the surrounding matrix (Forman and Godron, 1984; Turner et al., 1987). Patches, corridors and matrix directly influence the spatial patterns and flows in a landscape. Spatial scale also greatly affects landscape structure, heterogeneity, and connectivity.

Landscape structure is determined by the flow of materials, animals, energy, and water through the landscape elements of patches, corridors, and matrix. Factors such as patch size and shape, corridor characteristics, and connectivity work together to determine the pattern and process of the landscape. The arrangement of spatial elements, especially barriers, conduits, and highly-heterogeneous areas, determine the resistance to flow or movement of species, energy, material, and disturbance over a landscape (Forman, 1995). An optimum landscape has large patches of natural vegetation, supplemented with small patches scattered throughout the matrix. Alternatively, corridors in the matrix can provide most of the small-patch functions (Forman, 1995).

2.3.5 Landscape Components

Landscape ecologists use the three basic terms of matrix, patch and corridor (Figure 3) to define the spatial structure at a given scale. These simple structural element concepts are repeated at different spatial scales. The size of the area and the spatial resolution of one's observations determine what structural element one is observing. For example, at landscape scale, one might see a matrix of mature forest with patches of cropland, pasture, lakes and wetlands. Looking more closely at a smaller area, one might consider open woodland to be a series of tree crown patches against a grassy ground cover (Stream Corridor, 1998). Habitat patches and corridors are hence encompassed in a landscape at various ecological and spatial scales. The ecological level varies in the biological organisation from genetic to ecosystem and in spatial organisation from local to global (Aspinall, 1998).

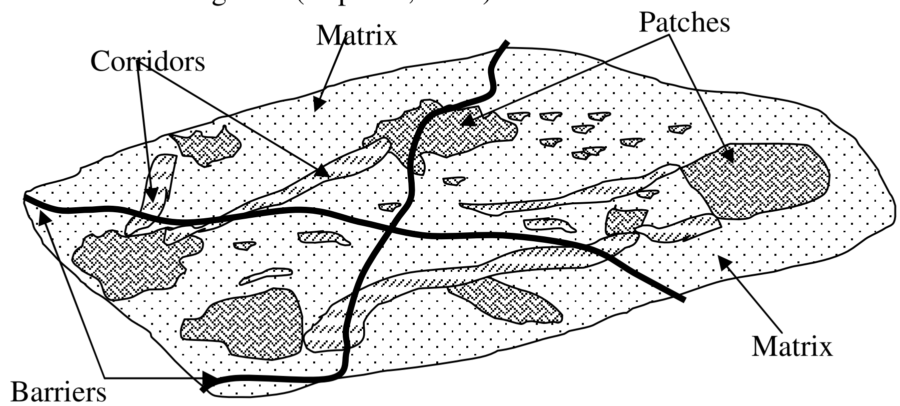

Figure 3. Conceptual view of matrix, patch and corridors in landscape

2.3.5.1 Matrix

Patches and corridors are imbedded in the matrix, which is usually the most extensive and connected landscape element present. However, the matrix may play a dominant role in the functioning of the landscape without being the most extensive landscape element. Determining what is the matrix in a landscape depends on connectivity, dominance, or function. Each landscape should be evaluated individually. The matrix in a landscape can be identified using sequentially the three prime attributes of area, connectivity and control over dynamics (Forman, 1995):

1. if one element type covers over half the area, or is much more extensive than the second largest element type then it should be considered the matrix
2. If the two are similar in total area then connectivity should be used to differentiate them. As defined the most connected element type could be described as the matrix

2.3.5.2 Patches and meta-population

Resource patchiness occurs when a habitat is divided into usable patches, which are separated from one another by non-usable habitat. Discontinuities can be created by opening land to agriculture, construction of buildings, dams, roads, power lines and other utilities. Often habitat loss and fragmentation, combined with the natural heterogeneity of landscapes, forces species to exist in multiple populations inhabiting relatively isolated habitat locations. Such a collection of populations of the same species is refereed to as meta-population (Merriam 1991). In landscape ecology, patches are spatial units at the landscape scale. Patches are areas surrounded by matrix, and may be connected by corridors. The geomorphology of the land interacting with climate factors, along with the other factors such as the establishment of flora and fauna, soil development, natural disturbances, and human influences work to determine patch size, shape, location, and orientation (Forman and Godron, 1984). The size, shape, and nature of the edge are particularly important patch characteristics (Forman and Godron, 1984).

A patch, in this study is a habitat, either occupied or unoccupied but has some potential as habitat (even if for a short time especially for migrating species). Three categories of patches are identified according to size (Figure 4):

Core area: A patch, which is big enough to provide habitats that can sustain and support most if not all of species requirements.

Stepping-stones: Are small patches in size that can be utilised by a migrating species for a short time but are not big enough to sustain the species.

Corridors: Are elongated patches that connect other patches.

2.3.5.2.1 Patch characteristics of interest

In a fragmented landscape the probability of a suitable patch being occupied increases with colonisation rate and decreases with increasing extinction rate (Forman, 1995; Vos, 1999). Although there are many factors that influence colonisation and extinction, connectivity and population size have been identified as the major factors. Population is dependent on the patch size and the specific species area requirement for reproduction and survival. Connectivity is in turn dependent on the inter-patch distance and the dispersal ability of the species. The main patch characteristics to consider in corridor design are the inter-patch distances and the patch size (area) which are important for species dispersal.

2.3.5.2.2 Landscape Connectivity

Connectivity refers to the degree to which absolute isolation is prevented by landscape elements, which allow organisms to move among patches (Merriam, 1991). It can vary from linear landscape elements providing only cover for moving animal species, to habitable patches that also provide reproduction opportunities. A spatial connection means either the patches are sufficiently close to allow movement between them, or there is a corridor along which organisms can move (Fahrig and Merriam, 1985). Sites in a landscape are connected if there are patterns or processes to link them in some way. These links arise either from static patterns (e.g. landforms, soil distributions, and contiguous forest cover) or from dynamic processes (e.g. dispersal and fire). Thus, the level of connectivity depends on the landscape configuration and the behavioural preference of the animals. Because most land mammals, reptiles and amphibians are limited to existence on or near the ground and prefer to occur in association with vegetation. They generally express a strong aversion to large expanse of water, concrete, bare soil or areas cleared off its natural vegetation (Saunders and De Rebeira, 1991). The particular required qualities of landscape elements, to enhance connectivity must be derived from basic biological knowledge of the species in consideration.

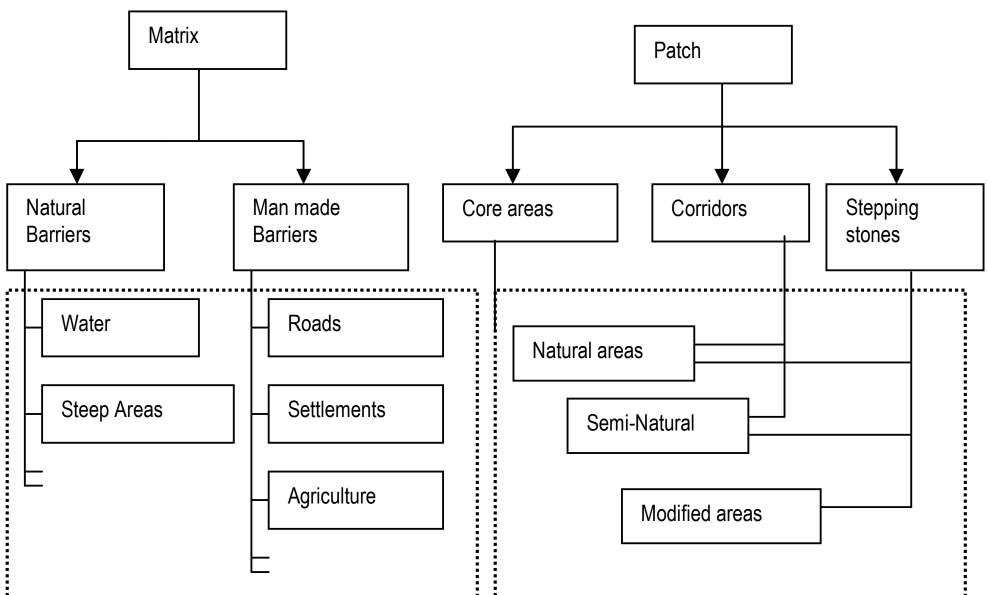

Figure 4. The classification of landscape elements into matrix, patches and corridors in relation to species dispersal.
(Legend: Core areas are most likely in natural areas; corridors may consist of natural and semi natural and stepping stones may consist of all types of areas. The barriers could either be natural or man made.)

2.3.5.2.3 Barriers

A barrier to the movements of species in a corridor is undesirable. It lowers the quality of the corridor. Roads more often than not run through many areas of species habitat and may be the most destructive cause of fragmentation (Fleury and Brown, 1997; Bohemen, 1998; Mladenoff et al., 1999). They interrupt connectivity and thus they require special consideration in the corridor design. The influence of roads as barriers has been demonstrated in studies in USA (Delibes, 1990). They have shown that wolf distribution can be related to density of roads passable by two wheel-drive vehicles. Wolfs generally do not occur in areas where road density exceeds 0.58 Km / Km^2. In contrast areas nearby with fewer roads were found to contain wolves. Other human related barriers include human settlements, dams, agriculture areas and related human activities (Figure 4) with varying barrier effect to species movement.

2.3.5.3 Corridors

Corridors are elongated patches that connect other patches together. They are typically defined as a nearly one-dimensional element in a two dimensional landscape that allows the movement of organisms between two terminal locations. A corridor can also act as a filter, only passing some fraction of the entering animals to the opposite end. Animals that use corridors can be grouped as either passage or corridor dwellers (Burbrink et al., 1998). Medium to large mammals and birds can be considered as passage species requiring only brief travel through the corridor. Amphibians and reptiles are corridor dwellers and need most or all their life cycle requirements in the corridor.

In general, corridors functions are summarised (Walker and Craighead, 1997) as: Avenues along which wide-ranging animals can travel, plants can propagate, genetic interchange can occur, populations can move in response to environmental changes and natural disasters, and threatened species can be replenished from other areas.

Within the general principles of landscape pattern, wide continuous corridors forming a green network are considered to be the best mechanism for maintaining connectivity (Figure 5). But a corridor need not consist of contiguous habitat. Many species such as birds use a corridor that may be composed of stepping stones (Figure 6) as long as the intervening matrix is not completely unsuitable for movement of key species (Forman 1995). Some stepping stones may be utilised as brief stops to rest, whereas others that are adjacent to good foraging habitat may be used for several days. Connection consisting of stepping stones only and land connection of short duration has been observed to filter the fauna. This result in unbalanced or highly biased subgroups of species. Essentially continuous dispersal corridors of habitat are preferred in which ecologically compatible species might extend their ranges (Harris and Scheck, 1991).

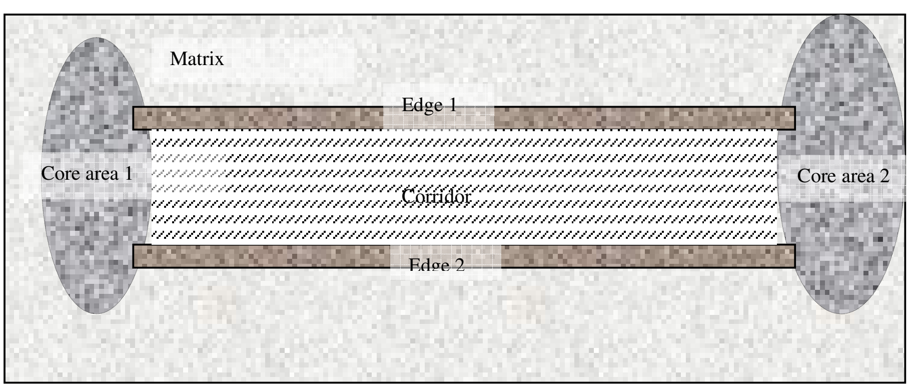

Figure 5. A conceptual view of continuous corridor

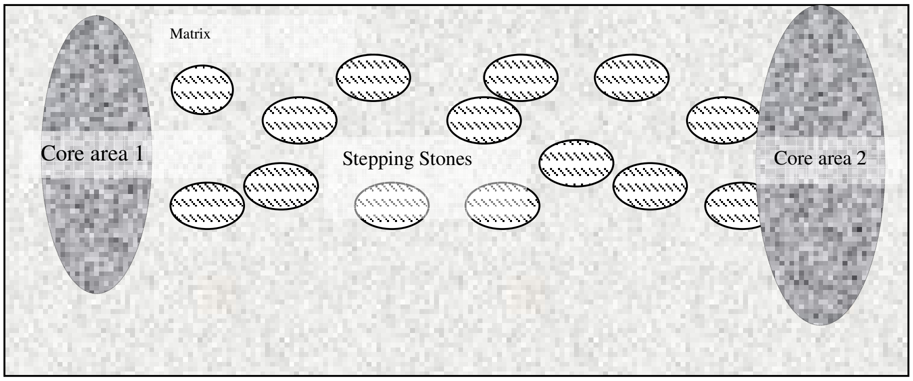

Figure 6. A conceptual view of stepping stones as corridors

Corridors frequently form interconnected networks across the landscape e.g. hedgerow networks (Cantwell and Forman, 1993). Corridor characteristics, such as width, connectivity, curvilinearity, narrows, breaks, and nodes control the important conduit and barrier functions of a corridor (Forman and Godron, 1984). These factors determine whether a landscape element is a barrier or a conduit to a particular species.

2.3.5.4 Disadvantage of corridors

Though corridors may have many advantages as conduits for migrating species they may have negative impact on populations in core areas which should be considered in the design (Burbrink et al.,1998):

1. if mortality rate is high it may act as a sink, by drawing animals from core areas to unfavourable conditions before arriving to the second core area
2. they might increase the probability that pests, diseases, exotic species and disturbances (e.g. fire) will spread to a patch

2.3.5.5 Corridors and Scale

At regional scales, corridors are viewed as pathways for the flow of genes over time. At landscape scale, they act as routes for individual animals moving between populations. At local scale, corridors are yearly or daily habitat for the animal survival and reproduction (Forman, 1995).

Choosing the scale at which one should observe the landscape will depend on the question at hand. Landscapes are dynamic mosaics that change over time. Seemingly, chaotic processes at one scale may be evidence of process or pattern when viewed at a larger scale. How we view a system of patches and corridors may be very different from how an organism utilises the patches and corridors within the landscape. Reconciling the differences in scale relationships is necessary in order to gain an understanding of the landscape dynamic. An exploration of several scales provides an opportunity to resolve domains, patterns, and processes, which interact to form the landscape. Means of assessing habitats at different scales using variable windows of analysis is described in (Riitters et al., 1996).

2.3.6 Quantifying habitat suitability.

The third consideration in habitat evaluation is the relationship between species requirement and the landscape components. This involves quantifying the suitability of each landscape element in relation to the species requirement. Habitat Suitability Index (HSI) is a unit-less value between 0 and 1 (Garcia and Armbruster, 1997). It estimates habitat conditions based on characteristics of land cover types. The value 1 represents optimum habitat conditions. The relationship between HSI and cover types can be described mathematically. This provides a means of quantifying the effect of different cover types to the species requirements. It can be approximated by combining layers such as current vegetation, topography (aspect, slope, elevation), distance to water, and perhaps climatic variables such as average temperature and precipitation. Because different wildlife species vary in their sensitivity to human disturbance, habitat suitability is constrained by disturbance variables such as distance to roads, distance to towns, traffic volumes and hunting status. Generally, information on known distribution of a species is also necessary for assessing the accuracy of the model. The species distribution (abundance) could be attained through aerial surveys, sighting, and radio-telemetry locations, hunter-kill and road-kill sites (American Wildlands organisation, 1997).

The attributes affecting habitat suitability and can be measured and manipulated easily using GIS include:

1. the amount in terms of area and size of habitat patches
2. the edge (perimeter) and shape
3. the distances (actual and weighted) between habitat patches

2.3.6.1 Suitability function development.

Habitat suitability index can be derived from a habitat suitability model. The development of a suitability model in concept seems simple, but there exists a problem. This arises from the fact that you cannot mathematically combine information that measures different things (i.e. physical characteristics within the environment). For example, you cannot add information classified by land use with that representing elevation or slope to define suitability. Mathematically the addition of these information types is meaningless. There are generally two approaches of generating suitability index, (Johnson and Host, 1991):

1. When the species requirements are known but the distribution is not known, the most frequently used approach is predicting relative suitability of the available habitat parameters. The assessment begins with the creation of a library of the relevant map themes e.g. (soils, land use, land cover, forest cover, elevation and possibly climatic). Specific parameters may be derived from source maps such as slope and aspect from elevation, infrastructure and human settlements from topographic maps. Individual parameters are then ranked to reflect the extent that, each variable contributes to or restricts the distribution of the target species. The ranking or weighting may be assigned both within and between variables using expert knowledge (Tamis and Zelfde, 1998). The thematic maps are overlaid and the ranking for all coinciding parameters at each location is summed up. The product is a map or table reflecting suitable or unsuitable habitat areas.

2. The second approach is used when species abundance is known with little knowledge of their requirements (Johnson and Host, 1991). The solution to this problem is a user-defined function that can convert the landscape measurements into suitability index. This function is estimated by the concerned disciplines using habitat parameters coinciding with known localities of the target species (Akcakaya, 1996). The function takes the form:

   Habitat Suitability Index (HSI) = F (Landscape elements).

Most methods of estimating the function, involve statistical procedures, using species occurrence or abundance at each location as the dependent variable and the habitat characteristics as the set of independent variables (De La Ville, 1997; Aspinall, 1998). The statistical procedures mostly used are stepwise multiple regression methods (including logistic regression) and stepwise discriminant function analysis.

2.4 GIS , Remote Sensing and Environmental Modelling

Most environmental and resource management problems have an obvious spatial dimension. Within the domain of environmental modelling, spatially distributed models that describe environmental phenomena in one, two or three dimension address this spatial aspect (Fedra, 1994). The basic elements used are biological species, chemicals and environmental media such as air, water and landscape elements. The state of these elements is expressed in terms of numbers, mass or energy and interaction dynamics. On the other hand, a GIS can handle spatial data by manipulating the stored spatial objects (Geometrical and thematic) represented as points, lines or area features.

Cartographic modelling language also known as map algebra is the most advanced GIS modelling environment (Albretch, 1996). Modelling with map algebra provides the ability to write algebraic equations in a raster environment between raster layers. It is more flexible and complete compared to overlay analysis techniques in a vector GIS. Additionally, the ability to develop a suitability surface in a raster environment allows for efficient modelling of site locations, such as the location of patches. Analysis in raster based systems is accomplished by the utilisation of basic mathematical functions. The GIS functions can be classified into five main categories (Albretch, 1996; Maguire and Dangermond, 1991) according to their utilisation (Table 2)

Table 2: GIS functions for environmental modelling.

TYPE	UTILISATION EXAMPLES			
Search	interpolation	thematic search	spatial search	re-classification
Location analysis	buffer	corridor	overlay	thiessen
Terrain Analysis	slope/aspect	catchment	drainage	viewshed
Neighbourhood Analysis	cost distance	nearest neighbour	proximity	zonal analysis
Spatial analysis	multivariate	shape	connectedness	patterns
Measurements	length	area	perimeter	

The overlap between the art of model building and the functions provided in GIS systems is apparent, and thus the integration of these two fields of research, technologies, or sets of methods, that is, their paradigms, is an obvious and promising idea (Fedra, 1994). An integrated system has the necessary power and flexibility to support environmental planning and management in practical applications.

2.4.1 Remote sensing and data capture

Vegetation cover is one of the basic data sets required in habitat studies (Tamis and Zelfde, 1998; Garcia and Armbruster, 1997). Information on vegetation can be more or less automatically, be derived from remote sensing data and further included in a multi-layer GIS. The quality or value of a vegetation map depends heavily on the selected method of vegetation classification and the purpose (Muller, 1997). The general method of mapping vegetation is by using some combination of digital image classification, photo-interpretation of satellite imagery, and reference to existing maps and ancillary data. The classification methods identified are based on taxonomy or physiognomy. The latter classification scheme is used, because it offers an accepted and useful hierarchical grouping that is based primarily on the structural expression of plant cover relative to environment as well as groupings by floristic composition. The physiognomic and floristic classification approach is important. It relates to animal habitat in terms of plant species assemblages, vegetation structure, climate, and plant morphology (GAP, 1996).

2.4.2 Image classification process.

Two fundamentally different methods are available for mapping vegetation namely computer-assisted classification and visual interpretation. The preferred method depends on the skills of the interpreting team, the extent and quality of existing base maps, ancillary data, and the spectral and ecological properties of the vegetation (GAP, 1996).

Classification is the transformation process of the remotely sensed pixel values into a number of classes. If this transformation process is based on specific knowledge of the object features and on decision rules in the feature space, it is called a supervised classification. As a preparation for supervised classification, one decides which objects must be classified and selects training fields. These fields are known objects, based on field visits or general knowledge of the area (Thalen, 1993).

Remote sensing techniques give information on the composition of vegetation species in arid regions in exceptional cases only. Such situations are virtually restricted to the occurrence of very large plants with a characteristic way of growing e.g. trees and shrubs. Certain information about vegetation can only be obtained by way of field sampling, for instance with respect to a complete composition of species and biomass assessment. Thus, reference observations in the field or ground truthing is mandatory (Thalen, 1993).

During the field visits vegetation morphology properties, structure and botanical composition, biomass, percent cover and stem counts are sampled (Rettie et el., 1997). After fieldwork, the preliminary interpretation map is converted into a vegetation map by integrating the results of field samples. The desired information for considering vegetation as a natural resource can be summed up as what grows where, when, how much and how good is it for that particular use?

2.5 Conclusion

This chapter has reviewed some of the important aspects related to habitat evaluation and the corridor properties. These concepts are important in the next step where they will be used and applied in delineation of corridors. They form the basis of the assumptions made about the movement requirement of a species and its modelling in a GIS environment.

3 MATERIALS AND METHODS

3.1 Introduction

Ecological corridor design is a process to identify and measure the suitability of landscape elements that define the corridor. In order to measure the suitability, it is necessary to understand the way individuals and local populations interact with it. The basic framework of corridor analysis consists of identifying areas of habitat, which are suitable for the wildlife species in question and the connection between them. Where this probable habitat connects areas of known (intended) population centres, it is often termed a corridor.

Habitat suitability depends upon the requirements of a given species. The evaluation can be an extremely difficult task due to the large number of criteria's and large volume of data (Miller et al., 1998). To use GIS to determine the suitable landscape spatial structure, first it is necessary to distinguish the habitat characteristics important for the species. The aim is to acquire and apply this spatial information through remote sensing and GIS respectively. By integrating disciplines and technologies, better information and maps will lead to improved planning and decision making and hopefully generate harmony between production to satisfy human needs and conservation across a landscape (Skidmore, 1998).

This chapter describes the GIS approach to suitable habitat mapping, detection and corridor design methodology. The role of GIS in various stages is explained.

3.2 The wolf model and data requirement

As discussed in the previous chapters, there are many constrain involved in the design of corridors. The problem can be formulated in terms of demand (species requirements which dictates the habitat suitability), supply (landscape elements suitability, measured using habitat function) and disturbance (presence of natural and human related barriers) in a corridor (Figure 7).

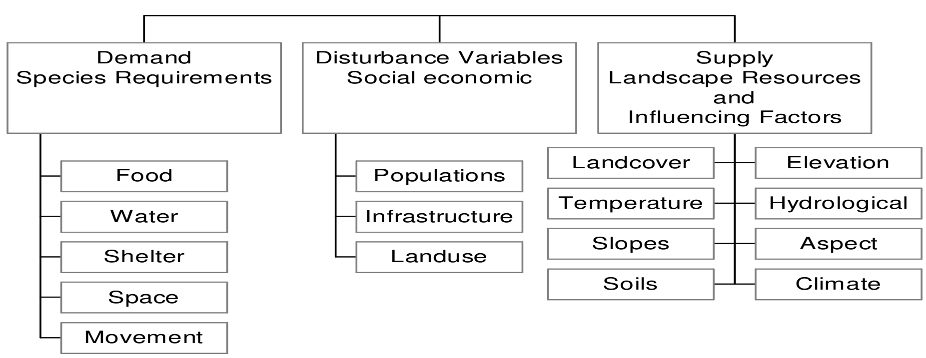

Figure 7. Species demand, supply and disturbance model

There is need to identify the problem based on parameters of space and location for GIS application. The processes of data management, analysis and display can then be supported by rules that are derived from the concerned disciplines which in this case include nature conservation, landscape ecology, land use planning, and animal ecology.

3.2.1 Wolf suitability model (function).

As explained in the introduction chapter, the basis for corridor design, in this study is habitat suitability analysis. The wolf habitat model adopted for this study was developed from worldwide wolf habitat mapping study (De La Ville, 1997).

The regression function takes the form:

$SI = 1 / (1 + e^{-z})$

Where

SI = Suitability index (probability of finding wolf in a given location)

Z **= 1.10 - 4.19***Road_Density **- 0.36***woody % cover (m) **- 0.10***human _density **- 0.06***herbaceous % cover (m) **+ 0.02***herbaceous % cover (n) **+ 0.07***woody % cover (n) **- 0.05***Average_Max_temp **+ 0.01*** elevation

And

m = Modified areas

n = Natural areas

The model is applied in a GIS environment by aggregating the existing land cover to fit the model parameters (Figure 10).

Statistical models are very dependent on the nature of the data set that is being used and the actual conditions of the sampled areas. Hence the application of this particular model is for the purpose of developing the GIS approach to corridor design and the processing model. The assumption is that, with availability of the right information, such a habitat statistical model could be developed for a specific region and applied in GIS environment using the developed approach.

3.2.2 Required data

The data sets required are:

- land covers types and their percentage cover
- human population distribution and density
- roads and railway lines types and density
- digital elevation model (DEM) for deriving elevation and slope
- climatic information (temperature)

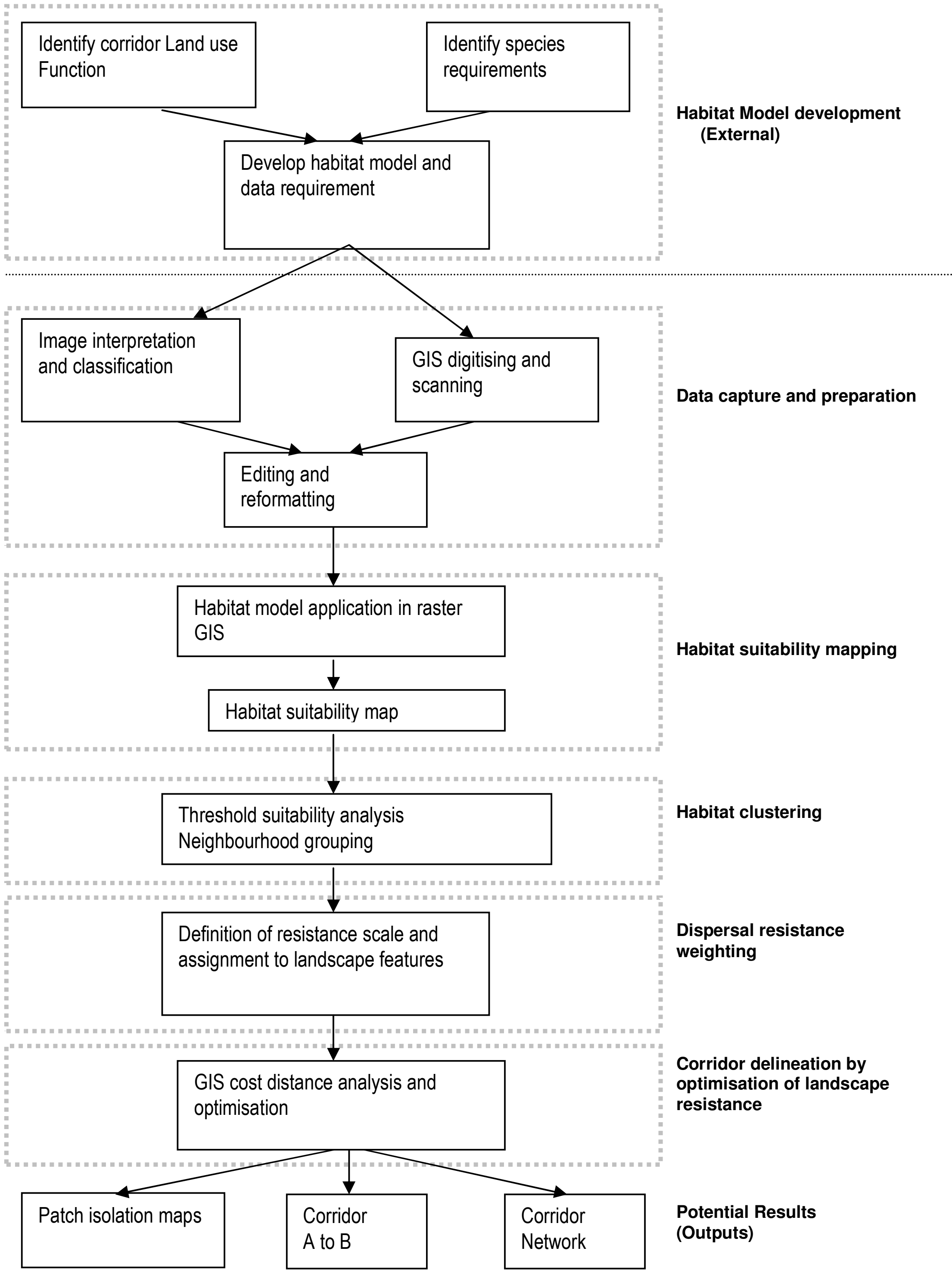

Figure 8. The proposed corridor design process model

(Legend: The figure shows the whole process that should be followed in corridor analysis from habitat model development to deriving potential corridors. The GIS model developed in this work does not include the development of habitat model, hence, only steps below the demarcation line are implemented in the process model.)

3.3 Design methodology and analysis process

After reviewing, identified stages of corridor analysis from two examples of (Fleury and Brown, 1997; Miller, 1998), corridor design stages can be summarised as:

- selecting projects goals and study swath
- identification of land use function of the corridor.
- understanding the regional context.
- spatial data collection and classification
- weighting values for various barriers
- data integration and analysis
- defining potential corridor locations
- output and evaluation
- creating and implementing site design and management schemes

The objective of the study has already been defined and the various aspects related to corridor requirements have been discussed in the previous two chapters. The following sections will concentrate on the remaining steps as shown (Figure 8); starting with regional perspective.

3.4 Study Area (regional context)

The study area is situated within the valley of the Guadalhorce River in Alora, Malaga, which forms part of province Andalucia, in southern Spain. The valley is part of the European Ecological Network (EECONET). It forms the eastern boundary of a core area which stretches out from the Atlantic coast in the East to the Guadalhorce valley in the West, comprising the ***Sierra de Grazalema and de Sierra de Ronda***. In the area North of Malaga, lie some smaller areas, which can be considered as stepping-stones to the large EECONET core area of the Sierra ***Nevada in the East*** (Figure 9).

The objective of EECONET is to conserve and enhance the ecological infrastructures in a region. The infrastructure in general consists of core areas, corridors and restoration areas (ECNC, 1998). The Guadalhorce Valley can then be considered as a corridor area between the two core areas mentioned above. This means the goal is to increase the area of the network, to provide temporary habitats, or facilitate dispersal and migration between the core areas.

The main aim is to determine the potential wolf habitats in areas made up of remnant forests separated by agricultural land and highways and to identify potential corridors through the barrier effect caused by highways, agricultural and settlement areas.

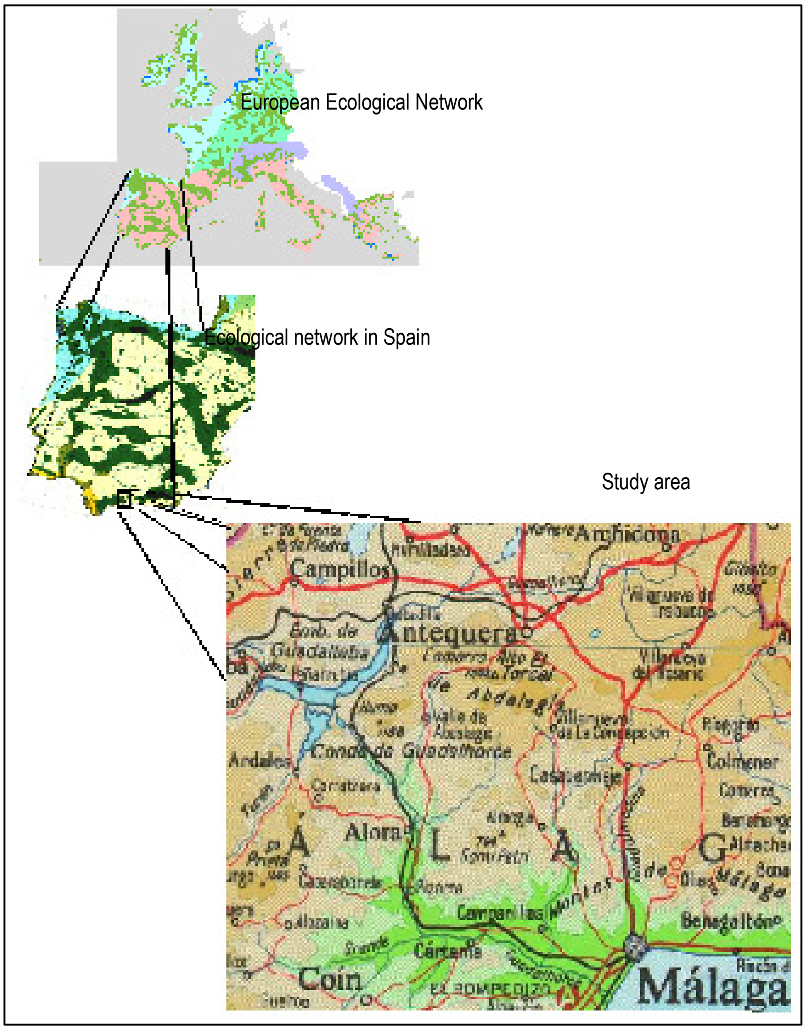

Figure 9. Study area location
(Legend: The Study area location in relation to the European ecological network at the continental and national level.)

This research has been carried out at local scale in which the future translocation routes of the examined species are to be created. From EECONET point of view, size is as crucial to the functioning of corridors as it is for core areas. No corridor should be less than 500 meters wide and those on a European scale should be several kilometres wide (ECNC, 1998). In this study, 500 meters distance is used as the basis for determining the size of analysis windows in the calculation of percentage land cover and the road density.

3.4.1 Land use and environment

Alora region has inter-digitated landscape having repeated interlocking mountain and valley systems with inter-fingering of rural land with strips of suburban development projects out from cities. It is divided into four major landform types (De Bruin et al., 1999) at the landscape scale namely:

1. Mountains ridges
2. Mountains with table tops
3. Hills
4. River valley

The climate is dry Mediterranean with an average annual precipitation of 531 mm and a dry period of 4 months between June and September. Elevation within the study area varies between 30 m on the south near Malaga to the high mountains of around 1500-m above sea level.

The main land use / land cover classes in Alora are agricultural lands (40%), natural and semi-natural (55 %) and unproductive areas (5%). The natural lands consist of herbs, shrubs and trees and semi-natural vegetation of planted trees e.g. pines. The unproductive lands consist of settlements, bare soils, rivers etc. The agricultural areas can further be classified into irrigated and rainfed. The irrigated areas are in the valleys with slopes of less than 5% where citrus is mainly grown. The rained crops are mainly olive and almond on the foot slopes and cereals, mainly wheat and chickpea on swelling and shrinking soils (marls) (Vd Berg, 1999). The available fauna includes; lynx (Lynx pardinus), wolf (Canis lupus), ibex (Capre pyrenaice), genet (Genetta genetta) and egyptian mongoose (herpestes ichneumon).

3.5 GIS approach to corridor design

The following section describes the GIS approach applied in the design of both potential habitats and corridor locations. The software packages used were ERDAS imagine for image processing, ARC/INFO for data capture and spatial analysis, ARISFLOW for process modelling and execution and ArcView for visualisation of results.

The approach is divided into four major steps:

1. data capture and measurement of landscape characteristics
2. application of habitat model to create suitability map
3. generating potential patch clusters and selection
4. finding potential corridor locations for selected patches

3.5.1 Data capture and transformation

Within GIS environment, data capture can be considered as the transformation of existing information to produce digital data if they do not exist. Remote sensing products (satellite imagery, aerial photographs etc.) in combination with image processing tools can be used to capture and prepare the necessary data for GIS.

Information contained in hardcopy maps is captured through manual or semi automated digitisation process.

3.5.1.1 Image processing and land cover classification

Reviewing properties of various types of satellite imagery for their utility to land cover mapping; Landsat Thematic Mapper (TM) offers the best overall source of digital data. Landsat TM has a spatial resolution of 30 by 30 m as well as having seven bands ranging from the visible, infrared and thermal infrared (GAP,1996; McCloy, 1995). Land cover for the study area was derived by performing a supervised classification on a resampled (15 by 15-m) 1995 TM image of the study area. This was achieved by performing a maximum likelihood classification, using auxiliary data from direct fieldwork observations, topographic maps and aerial photos. Nine categories of land cover types were identified. The cover types were distinguished as shown in (Figure 10). Several samples of training areas (signatures 2 to 4), for each cover type class were digitised from a screen display of bands 3,4 and 5 which has the best contrast for land cover mapping. These samples were used to classify the rest of the image.

The town and village classes were not included in the classification because of varied spectral reflectance within, causing un-realistic classification. These areas and the major water sources were digitised from 1:50000 scale topo maps and used to update the classified cover map.

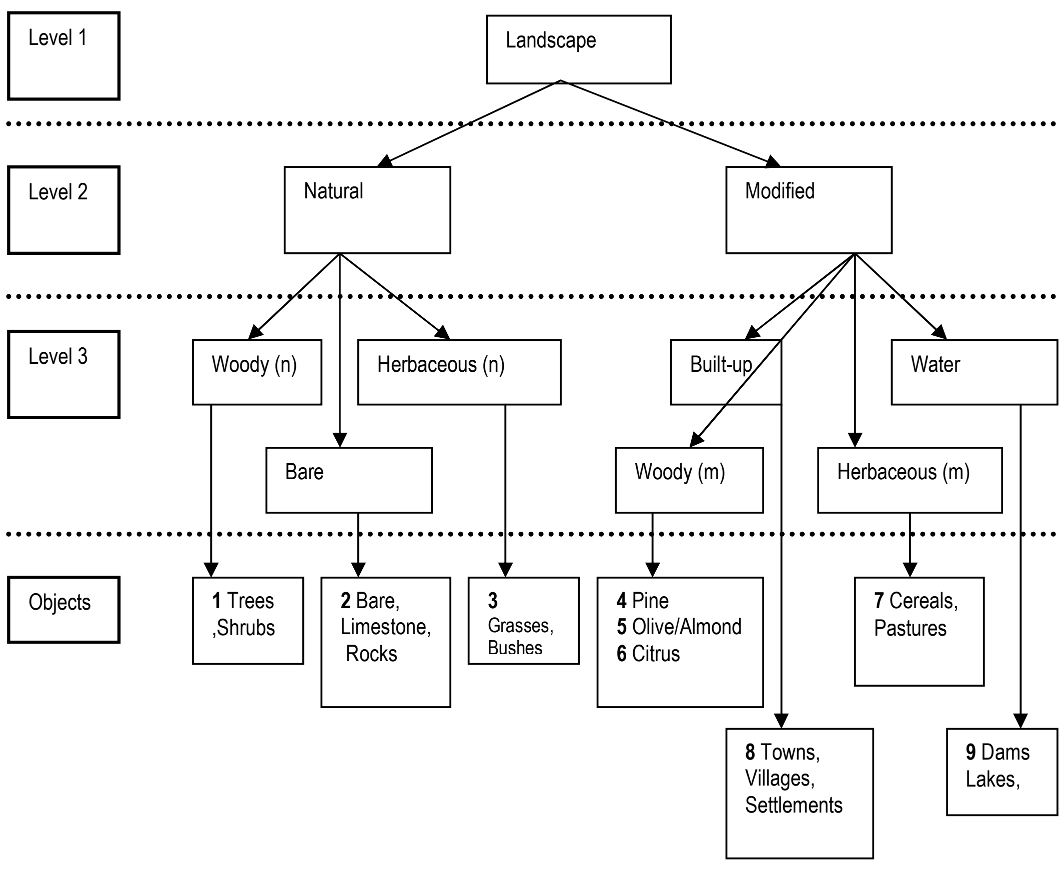

Figure 10. Land cover elements and the aggregation hierarchy for habitat model
(Legend: Natural - areas without or with very little human influence. Modified – areas of human related activities).

Note:

In the sections to follow, the symbols shown in (Figure 11) are used to represent the process action, process flow direction, input and output data of each procedure in the process model. The GIS name used is referred in the text using the same fonts e.g (Rastername)

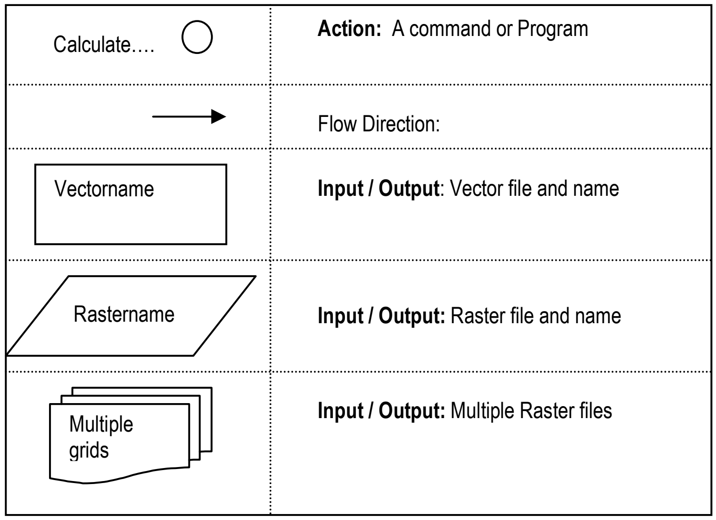

Figure 11. Symbol Legend

3.5.1.1.1 Percentage cover calculations

The percentage cover of a given vegetation type is describe as the proportion of the vegetation type within a given plot on the ground (Riitters et al., 1996). The definition of the plot size and shape depends on the question at hand and the scale at which the analysis is being performed. The processing of land cover grid involved two steps. In the first step the land cover map was separated into distinct GIS layers of each cover types showing the presence (1) or absence (0) of the cover type. In the second step the percentage cover of each cover type was calculated as in (Figure 12 and Appendix 1) using the following reasoning:

Let

F_z = Filter size = Number of rows * Number of columns

C_i = land cover type grid (1 or 0) within the filter window

Then percentage cover $C_{i\%}$ of the middle cell in the filter is calculated as:

$$C_{i\%} = (\sum Ci / F_z) * 100$$

Assuming a 5 * 5 filter window, then the value of various vegetation percent covers in the highlighted cell (Figure 12) is calculated as shown:

The resulting grids are stored for model application in the next step.

C1	C4	C4	C4	C4	C5	C5
C1	*C4*	*C1*	*C1*	*C4*	*C4*	C4
C4	*C2*	*C1*	*C2*	*C1*	*C4*	C3
C3	*C3*	*C1*	**C2**	*C1*	*C3*	C3
C3	*C2*	*C1*	*C1*	*C3*	*C3*	C5
C4	*C2*	*C3*	*C2*	*C3*	*C3*	C5
C4	C5	C3	C5	C5	C5	C5

C1 % = (8/25) * 100

C2 % = (6/25) * 100

C3 % = (7/25) * 100

C4 % = (4/25) * 100

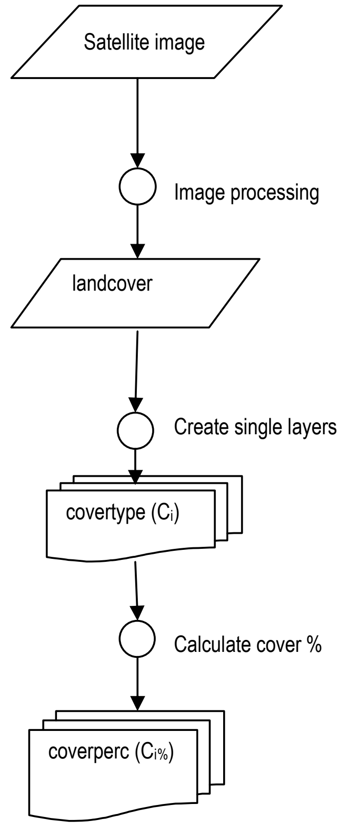

Figure 12. Percentage cover calculations process

(Legend: landcover – the derived land cover grid ; covertype – grid for a particular cover type ; coverperc – grid for percentage cover of a particular cover type)

A filter was applied to each of the layers where the cover percentage was derived from the proportion of each cover type within the window. A filter window of 33 by 33 (approximately 500 * 500 meters, by EECONET standards) was initially used. To demonstrate the influence of scale, analysis was also performed using a window size of 1000 meters.

3.5.1.2 Topographic data capture

The major source of topographic information is the existing topo maps. The available topo maps were scanned, geo-referenced and transformed into the existing map projection of Alora database. The data sets were digitised on screen using ArcInfo.

3.5.1.3 Road / Railway (Road/Rail) density calculations

Road density is a measure of human influence within the landscape. The impact of transportation channels on wildlife and landscape in general depends on the traffic intensity (Vos, 1999). To generate the density map, a digital fishnet (kmgrid) of size 0.5 by 0.5-km was created and overlaid with the digitised road/rail map (Figure 13). The lengths of road/rail in each grid was calculated (See Appendix 3). The lengths were arbitrarily weighted (Table 3) based on the road type to cater for assumed traffic intensity. The maximum traffic intensity is assumed to be on the primary roads and diminishes downward according to the road classification hierarchy (Table 3). The weight values can be changed depending on the availability of actual traffic intensity information and their influence.

Table 3: Road types and the traffic intensity weights used.

Road_Type	**Weight**
Primary Roads	1.0
Secondary Roads	0.8
Minor Roads	0.6
Railway	0.9

The calculations are made using vector data, in contrast to the cover percentage calculations, which are done using raster data. The resulting road/rail density vector map is converted to raster format for the next stage of analysis (Figure 13).

Let

F_n = Fishnet Area , L_{ai} = Road/Rail Length , R_{wi} = Road/Rail type weight

Then Road Density R_d

$R_d = (\sum(L_{ai} * R_{wi})) / F_n$ Km. / Km^2.

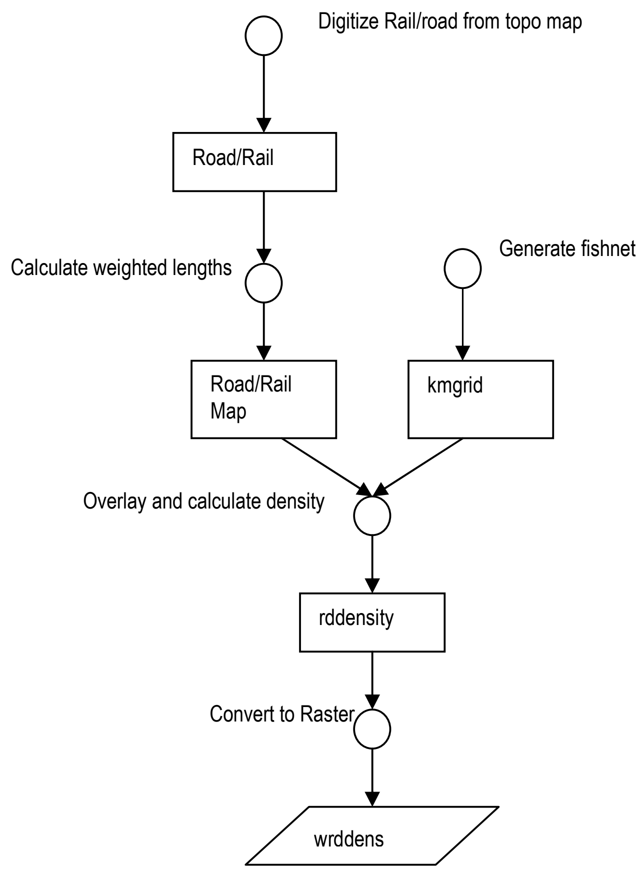

Figure 13. Road/Rail data transformation process
(Legend: kmgrid – the vector fishnet ; rddensity – Derived vector weighted road density ; wrddens – Derived raster road density)

3.5.1.4 Human population density

The important information regarding human population distribution is the sphere of influence according to population sizes in a settlement (Town, Village etc). The population density in Malaga province is about 164 pp / Km^2. This is quite high, compared to the provincial density of 82 pp / Km^2. In general the rural areas population density is like the provincial density of 79 to 82 pp / Km^2. (pp- persons per).

Generally, the population in the study area is concentrated in scattered towns and villages. There have been increases of sub urbanisation in high growth areas around the villages of Alora, Antiquera, Pizzara, Cartama encroaching the agricultural areas (Vd Berg, 1998).

The settlement areas are interconnected with a road and railway network. The density of the network is higher in the south toward the coastal areas, where many tourist attraction centres are located e.g. Malaga.

Due to unavailability of actual population distribution figures and maps, the resulting percentage cover grid of settlement (settmperc), from the filter analysis of land cover, is used to assign the population density (popgrd). Areas with the highest cover being assigned the population density of Andalucia and varying to zero where the cover percentage is zero (Figure 14).

Therefore Population density P_d

$$P_d = A_d * (S_{\%} / 100)$$

Where A_d is the population density of Andalucia and $S_{\%}$ is the settlement percentage cover.

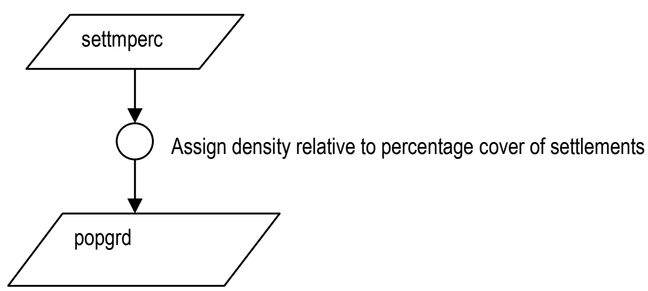

Figure 14. Calculation of human population density
(Legend: settmperc – settlement percentage cover grid; popgrd- derived population density grid)

3.5.1.5 Elevation and Slopes data sets

A Digital Elevation Model (DEM) provides a digital representation of a portion of the earth's terrain over a two dimensional surface. The basic data for a DEM is based on terrain elevation observations that are derived generally from one of three sources: digitised contours, photogrammetric data capture (including aerial photography and digital satellite imagery), and surveying. DEMs derived from contours are perhaps the most common of all sources. This is because digital topographic data have been developed from analogue maps for the longest time when compared with the other sources (UNEP/GRID, 1999). Contours from analogue maps are normally digitised using, either semi-automated line following, or automatic raster scanning. Subsequently the contours are edited and tagged with elevation values. The DEM is finally interpolated from the information using the available GIS functionality. In this research, an existing DEM of the study area is used to generate the required elevation and slopes data sets.

3.5.2 Application of habitat model to create suitability map

The parameters influencing the habitat suitability of wolf have been discussed in the previous sections and mainly consists of those that positively influence the habitat suitability (e.g. natural areas) and those that negatively influencing the habitat i.e. anthropogenic disturbances factors. The function was slightly modified to include the Bare/Rocky areas, which have been identified to be suitable for wolf especially for resting and hiding during day time (Delibes, 1990). These areas were arbitrarily grouped under natural herbaceous class and assigned weight of 0.02. Similarly, temperature data was not available, hence it was excluded from the analysis.

Thus new **Z**

> **= 1.10 - 4.19***Road_Density **- 0.36***woody % cover (m) **- 0.10***human _density **- 0.06***herbaceous % cover (m) **+ 0.02***herbaceous % cover (n) **+ 0.07***woody % cover (n) **+ 0.02***Bare/rocky **+ 0.01*** elevation

The model was applied in ArcInfo GRID raster model taking advantage of the map algebra facility (Figure 15, Appendix 4). All the input parameters were converted into raster format for the analysis.

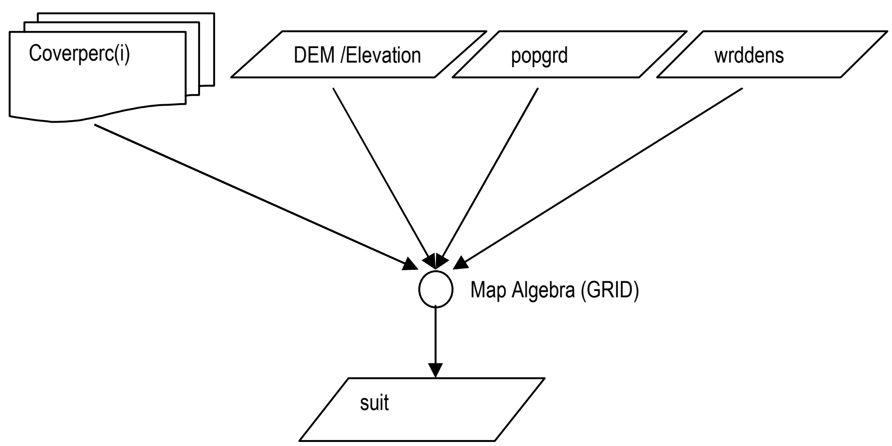

Figure 15. Wolf suitability function application process in GIS ArcInfo
(Legend: suit – Derived habitat suitability map for wolf)

There are two ways of representing geographic information in computer, namely vector or raster. Vector GIS are constructed of points, lines, and polygon objects. These objects are often referred to as line drawing objects because the GIS are constructed of traditional mapping objects. Raster based GIS uses cells to represent surface features. Modern GIS software allows for the conversion of data between the two systems.Raster GIS data have many advantages for surface modelling. In vector data models, habitat data can only be derived and stored as discrete sharply bounded and internally homogeneous polygons (Aspinall, 1998). This imposes fixed organisation for subsequent analysis. On the other hand raster based models provide a surface of variation and can be used to investigate generalisation and scale effects.

3.5.3 Generating potential patch clusters and selection

The potential patch clusters were generated from the suitability map created in the previous section. The recommended cut off suitability value is about 0.6 (De La Ville, 1997). Thus, the clustering was done only on cell values that are above this cut off value (suitover) (Figure 16). The selected cells were grouped into regions of contiguous suitable groups (suitrgn) and each group was assigned a unique identity number (Figure 16 and Appendix 7).

Next the average suitability (suitavg) and the total area (suitarea) were calculated for each group. Size as well as suitability is an important characteristic of a patch (Forman 1995; Fleury and Brown, 1997). A suitability and size factor (S) was calculated as a product of area and average suitability per identified group (avgarea).

S = Area * Average suit

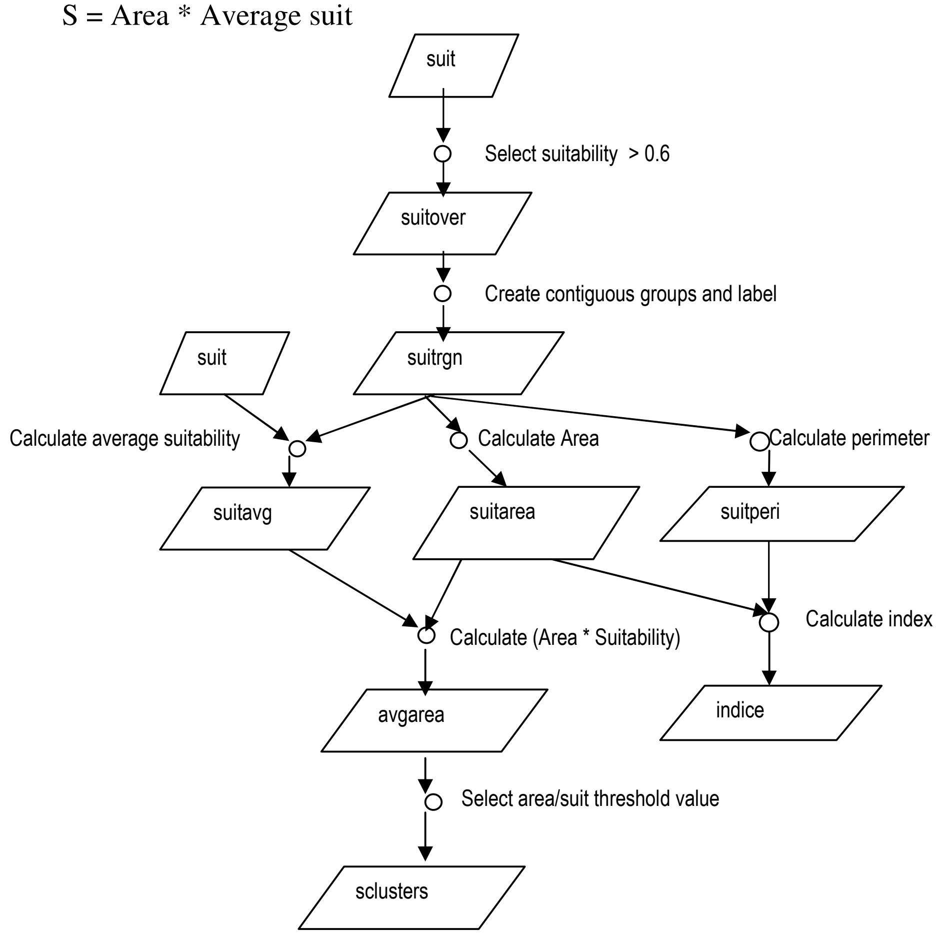

Figure 16. Suitable patch clustering process
(Legend: sclusters – Derived suitable patch clusters ; indice – Derived shape index)

The final suitable patches (sclusters) were selected as those satisfying (suitability * area) cut off value. In this case the threshold suitability is 0.6 increasing to about 1 and the expected minimum area was assumed to be 1 Km^2. The cut off value was calculated as 1 * 0.6 on the lower side of suitability. Conversely if the smallest area must be of the highest suitability then we can pick 1 * 0.9 as the cut off value. The model allows the adjustment of cut off value, which depends on the species area requirement.

The suitability of a patch also depends on the shape and edge characteristics. The patch area perimeter indices (indic) were calculated for each patch (Swetnam et al., 1998). Shape index Si = Patch perimeter / Perimeter of a circle with same area

If A is the area of the patch and P is the perimeter

Then $Si = (P / (2 * \sqrt{(A * 3.14)}))$

If the shape factor is important for a particular species, and the indices relationship is known, then, the factor can be used to reselect groups that satisfy the required shape factor. In this case study the factor was not used.

3.5.4 Modelling of corridors through the matrix

Metapopulation theory implies that although small populations suffer from the chance of extinction, a species can survive on regional level if local extinction is compensated for by re-colonisation (Vos, 1999). The possibility of patch re-colonisation is determined by connectivity of the metapopulations, which is dependent of the distance between suitable patches as well as the relative resistance of the landscape. The structure and the configuration of the habitat determine the resistance. One of the main functions of an ecological corridor is facilitating movement of organisms among the remnant patches of native habitats. The objective of corridor model is to delineate landscape routes offering the best chance of success for wildlife moving among the patches within the surrounding matrix. To accomplish the task of finding potential corridors, several assumptions had to be made in relation to landscape resistance and species behaviour.

3.5.4.1 Assumptions

- Many wildlife species have a tendency to avoid human and human related activities. Therefore landscape routes to be designated, as corridors should avoid such activities.
- Wildlife movements can take place in many types of habitats, even those that are not generally very suitable. But the assumption is that in general they would follow areas with suitable habitats so long as the intervening matrix is not a complete barrier for species movement. Such habitats would offer food and shelter for a short period of time.
- Species would take the shortest possible route (least resistance) between the patches as well as taking into consideration the above two assumptions.

3.5.4.2 Model components

The model for corridor analysis can be divided into four main components (Bowser, 1996) namely (Figure 17):

1. identifying transforming surfaces
2. applying an impedance weighting protocol on the surfaces
3. generating a single accumulated resistance surface

4. selecting various types of corridors on the surface

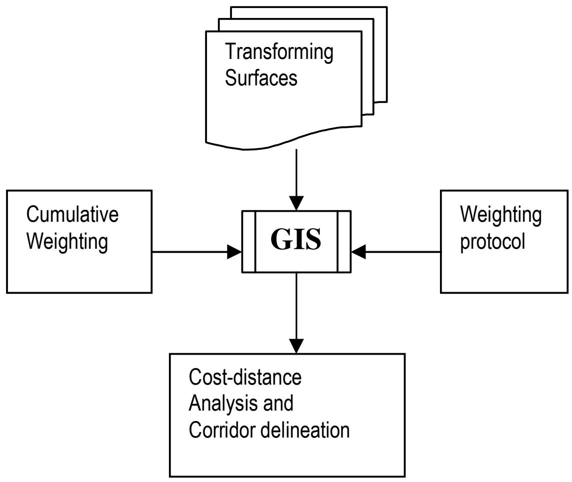

Figure 17. Corridor model components

3.5.4.3 Measurement of resistance

Within the GIS environment, the impediment power of spatial structure to the flow of materials can be modelled on the basis of pre-conceived concept on ecological impact (resistance) of identified features on animal dispersal.

Two methods of measuring resistance have been proposed (Forman, 1995).

1.) Since boundaries separating spatial elements are locations where objects usually accelerate or slow down, it has been suggested that boundary-crossing frequency i.e. the number of boundaries per unit length of route, is a useful measure of resistance.

2.) General measure could be simply the relative resemblance of a matrix to the optimal habitat for a species. Therefore, area could be divided into suitability classes of habitats, so the amount of less suitability is a measure of resistance.

In this study the second method was applied in assignment of landscape resistance. The landscape was divided on the basis of suitability map derived (see 3.5.2) and assigned resistance values as explained below.

3.5.4.3.1 Transforming surfaces and weighting protocol

These are GIS based layers on single environmental feature that have influence on animal dispersal. The two main transforming surface parameters used were the habitat suitability map from the habitat analysis results and slope percentages derived from the existing Alora DEM.

The weighting protocol on the transforming surface is based on the ecological impact of the feature on animal dispersal. A resistance scale range between 0 and 100 is used. The habitat suitability index is the basis of weighting protocol. This is used together with other parameters not considered in the habitat suitability model (Figure 18, Appendix 6).

Resistance (R_f) = F (Habitat suitability, Slope, Settlements and Lakes)

The resistance to species movement with respect to habitat suitability is assumed to have an inverse relationship. Thus, the suitability level was stretched within the resistance scale (0 –100) in an inverse manner.

$$R_{hs} = (1 - S_t)*100$$

Where R_{hs} is the resistance value due to un-suitability and S_t is the suitability index varying between 0 and 1.

The slope percentage was classified into 6 classes as shown (Table 4).

Table 4: The slope percentage class range and description (Adapted from Vd Berg, 1999).

Slope (%)	**Description**
0 -2	level to nearly level
2 -8	undulating
8 -16	rolling
16 –30	hilly
30 – 60	steep)
Over 60	very steep

It is assumed that very steep slopes have influence on the dispersal of the wolf. The slope values in this class were used directly as dispersal resistance (R_{sl}). The rest were assigned a value of zero resistance.

$$R_{sl} = \text{(Slope percentage in very steep areas)}$$

Including the resistance aspect of lakes (R_{lk}) and the actual settlement areas (R_{st}) was necessary, which in this case are considered as complete barriers. These two land cover types were assigned a maximum resistance value (100) to exclude them from the possibility of being designed part of corridor locations.

The final dispersal resistance per grid (R_f) was derived as:

$$R_f = R_{hs} + R_{sl} + R_{lk} + R_{st}$$

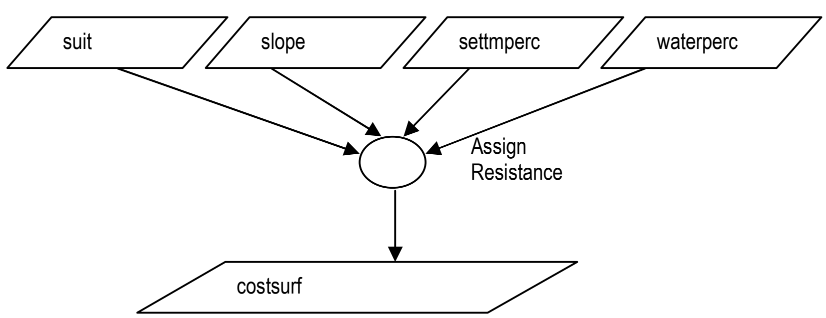

Figure 18. Resistance surface preparation process
(Legend: waterperc – water percentage cover; costsurf – Derived final resistance surface; slope – slope in percentage derived from DEM)

3.5.4.4 Dispersal corridor location

Three possible types of analysis were performed to indicate the potential corridor locations.

3.5.4.4.1 Patch isolation analysis:

Habitat isolation has been described as one of the causes of species population decline and even extinction. To identify and measure the isolation of patches, an accumulated resistance surface was derived (clustdistance) (Figure 19, Appendix 8) with all the identified patches as source points. The weighting protocol and the impedance surface were derived as above (section 3.5.4.3.1). By reclassifying the resulting surface the isolation of patches could be viewed on the resulting map (isolate). The reclassification was done interactively in ArcView by trying various classes to view the isolation effect.

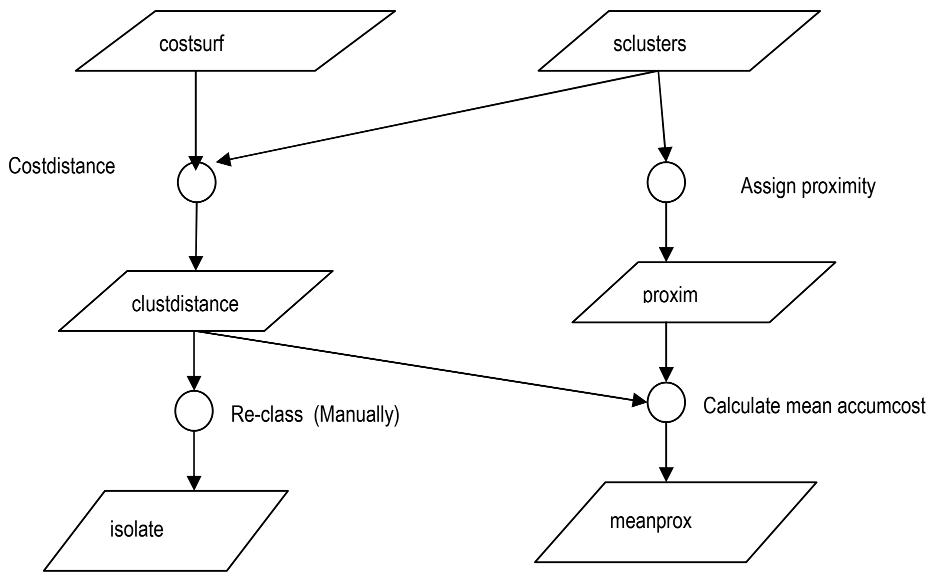

Figure 19. Patch isolation analysis process

(Legend: clustdistance - accumulated resistance of moving from a point to the nearest patch; isolate –patch isolation; proxim – patch proximity; meanprox – mean accumulated resistance within the proximity of a patch)

To quantify the isolation, a proximity map to the patches was computed (proxim). This was used to summarise (mean) the accumulated resistance within the proximity of each patch as a map (meanprox) and in tables. The patches were ranked according to the calculated mean values (See results Table 7 & 8 , Figure 25 & 26).

3.5.4.4.2 Optimal route between two patches

The best location for the dispersal route depends on the expected source(s) and destination(s) points. By visually checking the patch clusters, general suitability, and the land cover maps, one is able to observe a general route of potential corridor. As explained in section 3.4, the study area is a transition zone between two core areas. The idea is to find the route with the least accumulated resistance through the resistance surface (optimum route). The process model requires the identity of these patches. Any two patches can be selected as source or destination.

Two suitable patch locations on the extreme end of the study area were picked as the source and destination for route analysis (dest1grd and dest2grd) (see Figure 20, Appendix 8). Accumulated resistance surfaces were created from one patch to the other and vice versa (costaccum1 and costaccum2). The two surfaces were added up to come up with a surface of relative accumulative resistance values in moving between the two selected locations (corridpath). The specific potential corridor route was finally mapped by reclassifying the resulting surface through trials of different classes (potcorrid) (See Figure 27). The minimum class forming a set of contiguous cells between the two patches is hence a potential corridor route.

3.5.4.4.3 Corridor networks

Corridors can also form a network between the suitable patches (see Figure 20, Appendix 8). This was achieved by computing two least resistance paths (costpatha and costpathb) between the two extreme patches (as identified in 3.4.4.4.2). Thus when one patch is selected as a source, the remaining patches are automatically selected as the destination (Appendix 8 and 9). The paths were combined into one least resistance path (leastpaths). The paths are created as lines (single cell). To view the paths as routes, an accumulated resistance grid, using the paths as the source and applying the previously created cost surface was derived (accumpaths). The potential corridor network (potnetwork) was again mapped by reclassifying the resulting surface through trials of different classes (See Figure 28).

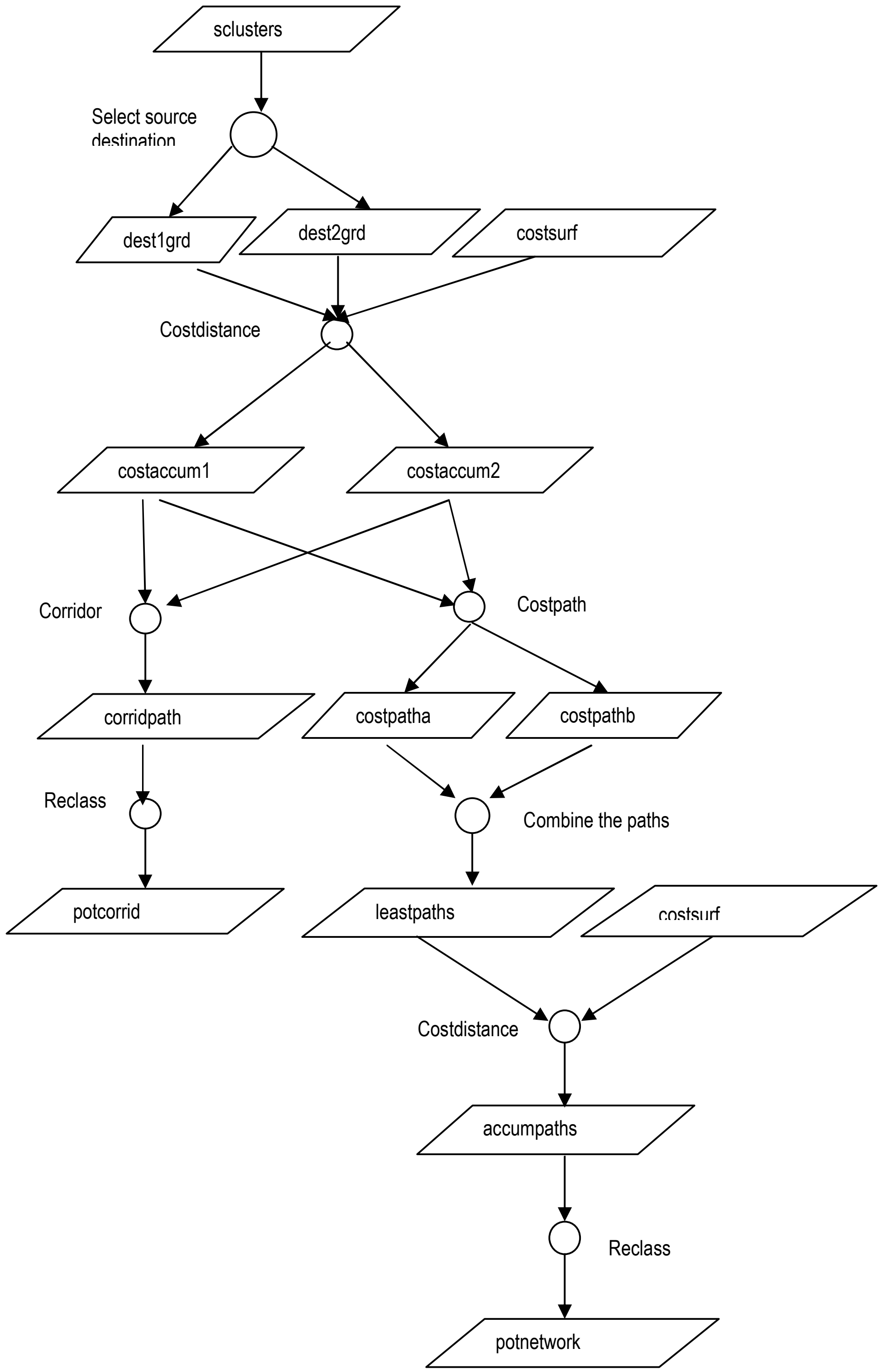

Figure 20. Corridor generation process

(Legend: dest1grd , dest2grd – source and destination patches; costaccum1, costaccum2 – accumulated resistance from either of the patches ; corridpath - sum of the two accumulated resistance surfaces ; potcorrid – reclassified map showing potential corridor between the two patches ; costpatha , costpathb – least resistance paths between the extreme patches ; leastpaths – combined resistance paths; accumpaths – accumulated resistance surface from the combined paths; potnetwork – reclassified map showing potential network)

4 RESULTS AND DISCUSSION

4.1 Introduction

An interactive GIS process model that can assist in corridor analysis was developed. Suitable habitats and corridors for wolf were delineated in the Alora case study area. These are only potential and may be a dispersing animal could use them. It can be claimed that if the species use the designated regions, then it will encounter fewer obstacles and its chance of survival may be higher. The accuracy of the results depends very much on the availability of quality data to be used and the ecological assumptions made. Data quality is still an important issue, particularly where outputs from GIS processing are used to support decision that may affect the survival of a threatened species, or the balance between land for conservation and economic development to sustain rural communities.

Hence, the results presented and discussed here are to demonstrate the application of the process model and do not claim to reflect the exact true state of the situation on the ground.

4.2 Results

The results are divided into six sections:

1. land cover classification results
2. the GIS process model
3. wolf suitability map and patches
4. patch isolation within the study area
5. potential corridor across the study area
6. potential corridor network within the study area

4.2.1 Land cover classification

Nine land cover types were mapped (Figure 21). The modified areas covered about 50 % and they are the most connected areas when considered as a group (Table 5). Hence, we can assume this to be the matrix in the region consisting mainly of agricultural activities, pine plantations and the settlement areas.

Table 5: Land cover types in Alora and relative area cover

Major Class	Cover type	ID	Cell Count	Percentage Cover	
Modified	Cereals/Grass	25	552,441	11.2	
	Olive/Almond	26	914,462	18.6	
	Citrus	29	337,280	6.9	
	Pine	24	406,235	8.3	
	Settlements	30	62,828	1.3	
	Water	22	100,448	2.0	**48.3**
	Lime/bare	23	428,657	8.7	**8.7**
Natural	Natural vegetation	27	1,331,378	27.1	
	Semi-Natural	28	729,263	14.8	**41.9**
	Unclassified	0	53,628	1.1	**1.1**
Totals			4,916,620.0	100.0	**100.0**

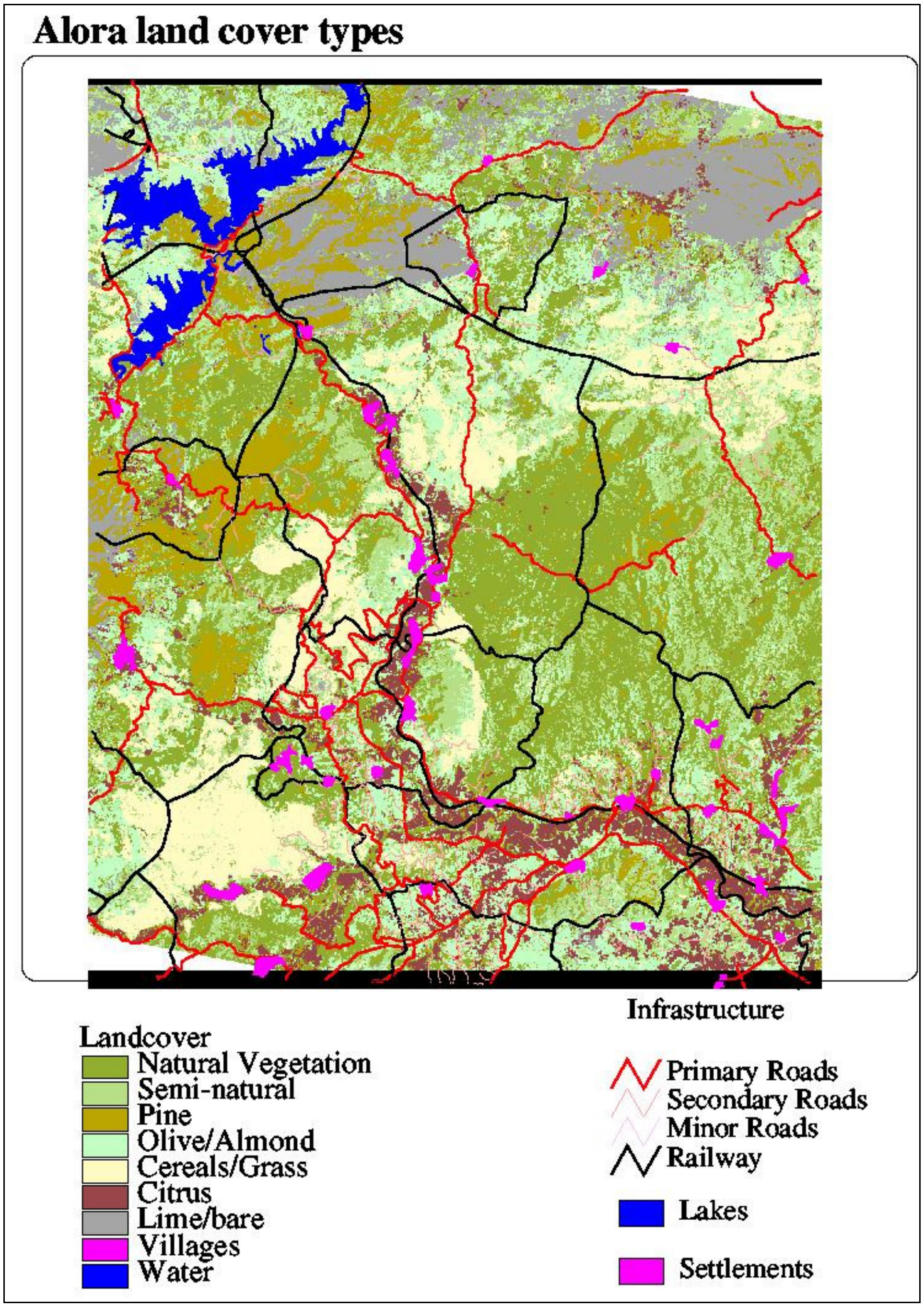

Figure 21. Land cover map (Source, Landsat TM, 1995)

4.2.2 GIS process model

The process model consists of independent macro (arc macro language AML) programs made to accomplish different tasks in corridor design (See appendices). The task of image processing could not be programmed, as it required complicated user manipulation techniques, which was difficulty to automate. Hence, the model was prepared within the GIS environment only. Within the model, a data action programme was prepared (in Arisflow) to bring together all the spatial analysis tools required (Appendix 9). This was necessary to simplify the application by allowing the user to control the flow of the process and change the input variables as required. The results of the executed parts are stored allowing the user to run the macros as individual steps. Therefore the previous steps do not have to be repeated for each model adjustment. The main drawback is that, the amount of storage and processing power required is quite high (Appendix 9). This could be a limiting factor where computer resource is not adequate.

The following steps of the model allow the user to adjust the model parameters:

1. The analysis window sizes for the calculation of vegetation percentage cover and road density, and the subsequent analysis at the scale of user's choice.
2. The weighting factors in the analysis of road/rail length and hence the calculation of density.
3. The threshold, suitability value as dictated by the statistical function used.
4. The threshold, (area * suitability) value to cater for area (or space) requirement of a species.
5. The assignment of resistance weights to the transforming surfaces.
6. The selection of source and destination patches for corridor delineation.
7. And finally, the reclassification processes for the creation of patch isolation maps, potential corridors and corridor network.

By adjusting the variables mentioned above, the user has the possibility of generating different scenarios for the corridor design process.

4.2.3 Wolf habitat suitability map

The habitat suitability function was applied in the GRID environment of ArcInfo to create the suitability map (Figure 23). The suitability map was divided into ten equal interval classes (Table 6). The areas above threshold suitability value of 0.6 cover 29 % of the total area. The percentage of cells within different suitability classes is as shown (Table 6). The graph shows a sharp boundary between the least suitable, moderate and very suitable areas (Figure 22). This might be an indicator of high level of habitat fragmentation within the study area.

Table 6: Sizes of different suitability classes. (TH –threshold class) and the grouping of classes above and below threshold value.

Class ID	Suitability Class Range	Cell Count	Percentage	Cumulative Percent	Grouping
1	0.0 - 0.1	3,206,607	64.4	64.4	71 % below suitability threshold value
2	0.1 - 0.2	118,078	2.4	66.7	
3	0.2 - 0.3	72,492	1.5	68.2	
4	0.3 - 0.4	57,886	1.2	69.4	
5	0.4 - 0.5	53,490	1.1	70.4	
6	0.5 - 0.6	52,586	1.1	71.5	
TH Class 7	0.6 - 0.7	58,950	1.2	72.7	29 % equal or above the threshold value
8	0.7 - 0.8	71,116	1.4	74.1	
9	0.8 - 0.9	107,390	2.2	76.3	
10	0.9 - 1.0	1,182,745	23.7	100.0	

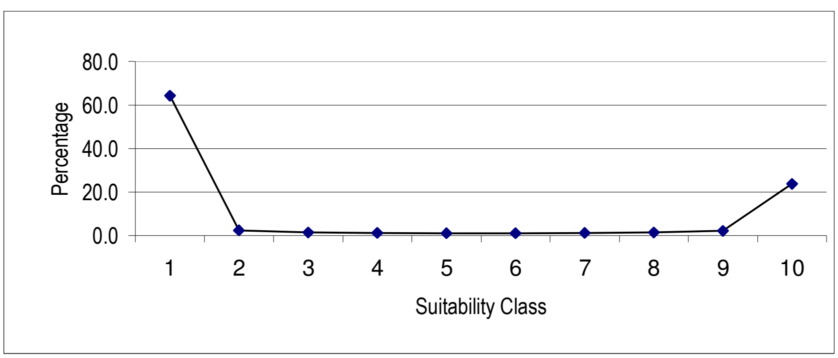

Figure 22. Graph of suitability classes versus area size in percentage

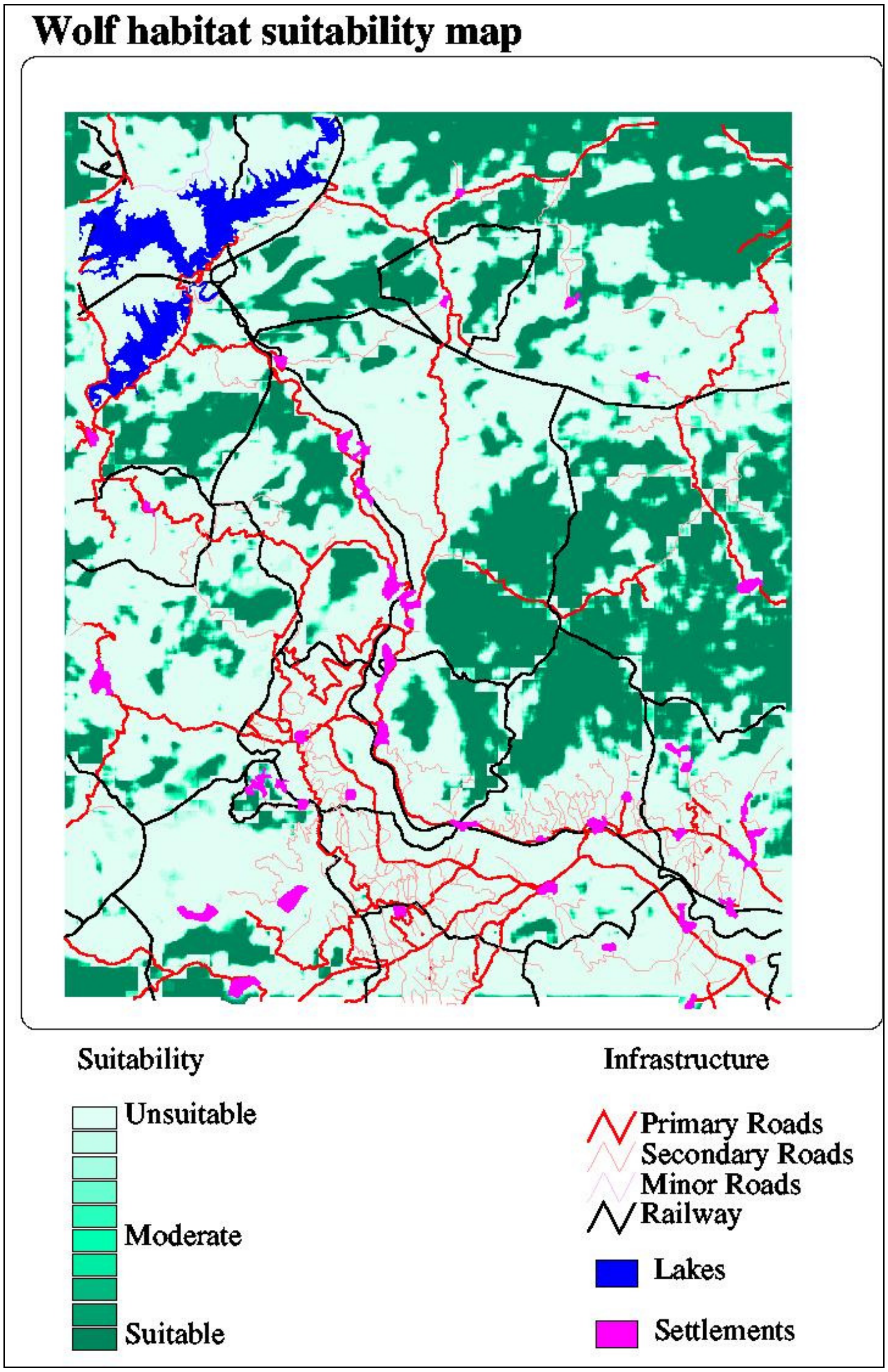

Figure 23. Wolf habitat suitability map

4.2.4 Patch isolation within the study area

Suitable areas (above 0.6) were selected and grouped into patches of suitable habitats. A total of 474 contiguous patches were identified with areas ranging from as low as 0.000225 Km^2 (one cell) to a maximum of 136 Km^2 (Figure 24). The final patch clusters were selected for those patches above threshold of (area * suitability) (Figure 25). A total of 26 Clusters were identified (Table 7).

Shape indices (Patch perimeter / Perimeter of a circle with same area) was calculated for each patch as shown in (Table 7).

To map and measure patch isolations, a map of accumulated resistance between all the patches was generated. Using re-classification, patch isolation can be displayed graphically for interpretation (Figure 25). An isolation factor was calculated for each patch as the mean accumulated resistance of cells within the patch proximity (Table 7).

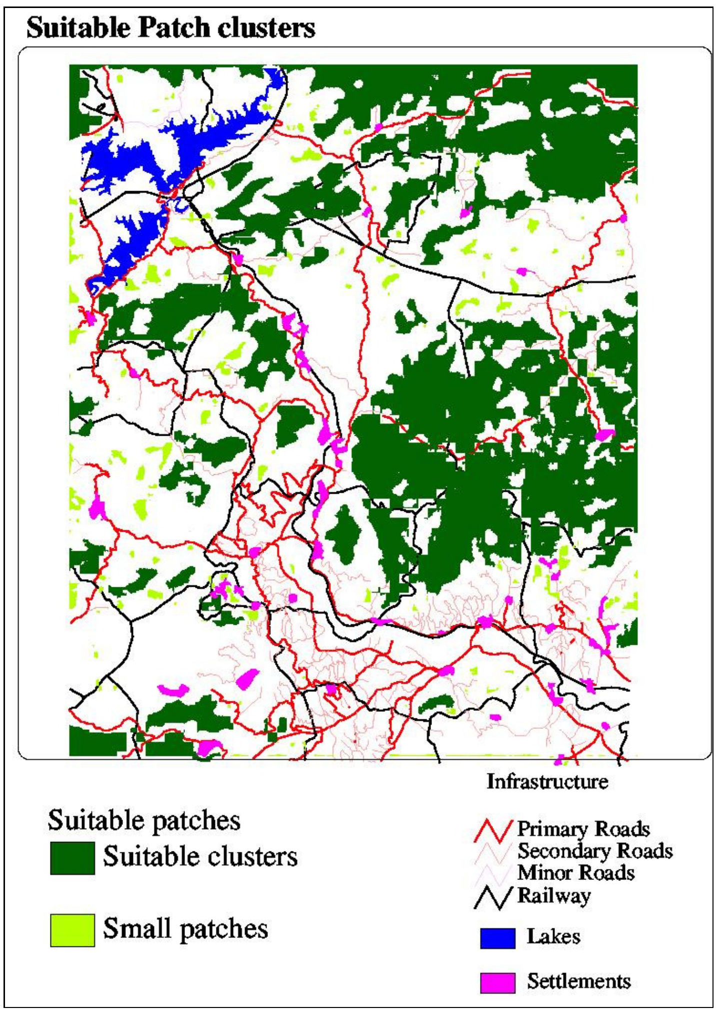

Figure 24. All derived contiguous patches
(Legend: A total of 437 patches were identified, with only 26 classified as suitable clusters, the rest were small patches in size, below the cut off value)

Table 7: Properties of suitable patch clusters using an analysis window of 500 by 500 meters

(Shape index = patch perimeter / perimeter of a circle with the same area, Cell count = Number of cells of 15 by 15 m making up the patch.)

Patch_Id	Cell_count	Perimeter in meters	Area in square meters	Shape index	Mean Accumulated resistance within patch proximity
420	4,998	8,550	1,124,550	2.28	3,047
442	4,122	7,650	927,450	2.24	2,244
454	3,182	7,560	715,950	2.52	1,830
55	6,003	6,810	1,350,675	1.65	1,825
21	31,113	42,510	7,000,425	4.53	1,627
317	14,303	13,260	3,218,175	2.09	1,468
394	6,095	12,660	1,371,375	3.05	1,464
443	21,962	17,760	4,941,450	2.25	1,106
364	6,470	11,340	1,455,750	2.65	1,097
455	17,582	9,690	3,955,950	1.37	1,073
113	4,159	5,700	935,775	1.66	1,012
166	6,007	10,650	1,351,575	2.58	966
147	70,544	64,260	15,872,400	4.55	963
292	10,960	23,130	2,466,000	4.16	961
363	3,909	6,990	879,525	2.10	912
243	7,458	14,910	1,678,050	3.25	870
171	27,196	25,560	6,119,100	2.92	830
255	13,380	10,770	3,010,500	1.75	799
340	9,420	12,990	2,119,500	2.52	779
274	15,234	18,390	3,427,650	2.80	704
59	25,498	35,400	5,737,050	4.17	633
63	65,092	67,110	14,645,700	4.95	597
174	605,047	432,570	136,135,568	10.46	497
60	23,325	32,310	5,248,125	3.98	347
463	13,746	16,650	3,092,850	2.67	332
1	321,944	203,700	72,437,400	6.75	241

From these tabular results and the map (Table 7 and Figure 25), a conclusion can be made that, patches on the southern part of the study area are highly isolated compared to the ones in the north. This is due to the presence of the intensive road network and many settlements in this part of the study area.

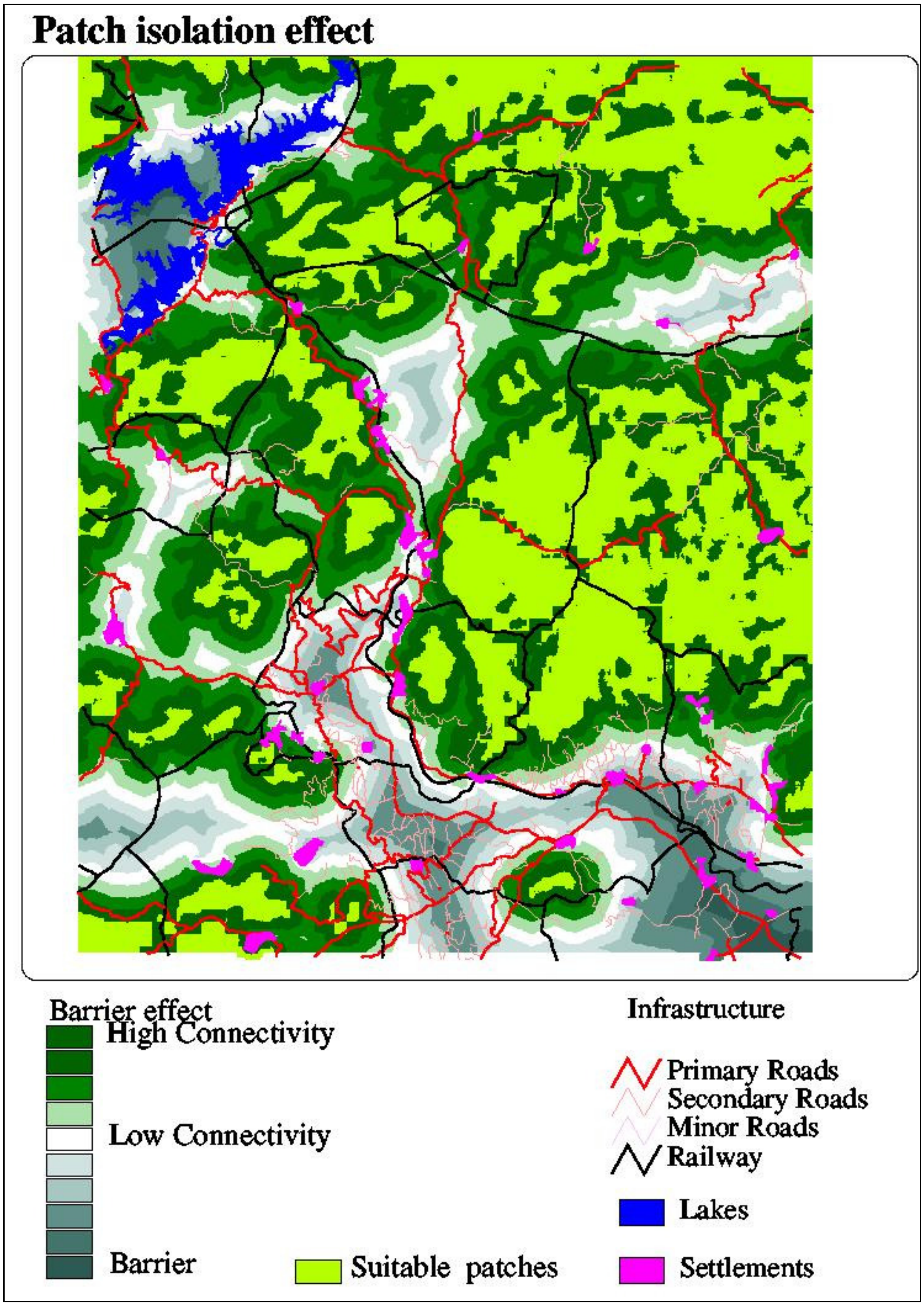

Figure 25. Suitable patches and isolation using analysis window of 500 by 500 meters

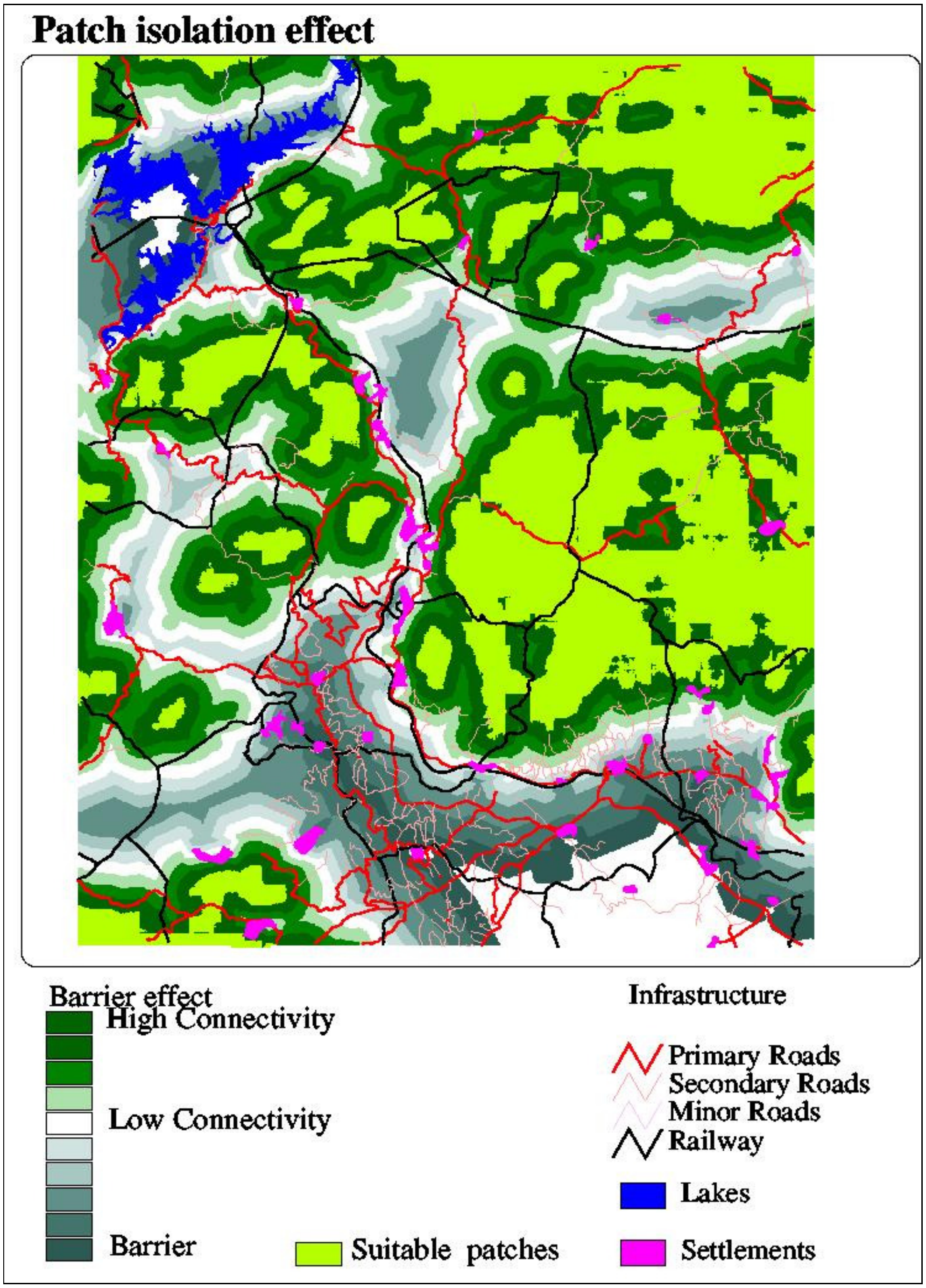

Figure 26. Suitable patches and isolation using analysis window of 1000 by 1000 meters

The results of analysis using a window of 1000 m are as shown (Figure 26, Table 8). In general the patch boundaries are more smooth and clear compared to 500-m window size. The number of suitable patches decreases, remaining with larger patches only. This shows that when viewing at small scale (viewing a large area) most of the small patches identified in a bigger scale become insignificant.

Table 8: Properties of suitable patch clusters using an analysis window of 1000 by 1000 meters

(Shape index = patch perimeter / perimeter of a circle with the same area, Cell count = Number of raster grid cells of 15 by 15 m making up the patch)

Patch_Id	Cell_count	Perimeter in meters	Area in square meters	Shape index	Mean Accumulated resistance within patch proximity
306	4,366	9,660	982,350	2.75	4565
12	15,571	14,760	3,503,475	2.23	2791
234	11,439	10,080	2,573,775	1.77	2566
26	3,924	5,040	882,900	1.51	2467
77	9,522	15,150	2,142,450	2.92	2193
329	51,933	43,230	11,684,925	3.57	2148
30	8,669	10,470	1,950,525	2.12	2015
276	4,056	7,080	912,600	2.09	1858
89	611,643	308,700	137,619,680	7.43	1422
83	3,380	7,020	760,500	2.27	1418
1	7,972	14,790	1,793,700	3.12	1416
206	5,137	10,260	1,155,825	2.69	1410
39	4,374	6,900	984,150	1.96	1309
186	11,864	11,040	2,669,400	1.91	1208
159	5,496	9,030	1,236,600	2.29	1164
70	73,784	52,350	16,601,400	3.63	1127
165	9,713	9,000	2,185,425	1.72	1031
254	6,943	8,220	1,562,175	1.86	1023
59	7,527	8,970	1,693,575	1.94	882
25	45,364	32,370	10,206,900	2.86	679
29	18,965	17,430	4,267,125	2.38	652
34	3,974	6,930	894,150	2.07	521
5	334,885	136,440	75,349,128	4.44	366

4.2.5 Potential corridor across the study area

The study area has been defined as a translocation region between two core areas (see section 3.4). The largest suitable patch identified is only 136 Km^2. This is not a viable habitat in terms of size for wolf (see section 2.3.2). Hence, there was a need to generate potential corridor across the area. The two extreme patches selected for corridor analyses are located as shown in red (Figure 27). The dispersal resistance is shown in shades of green with dark green showing routes with the highest potential of being designated, as corridors.

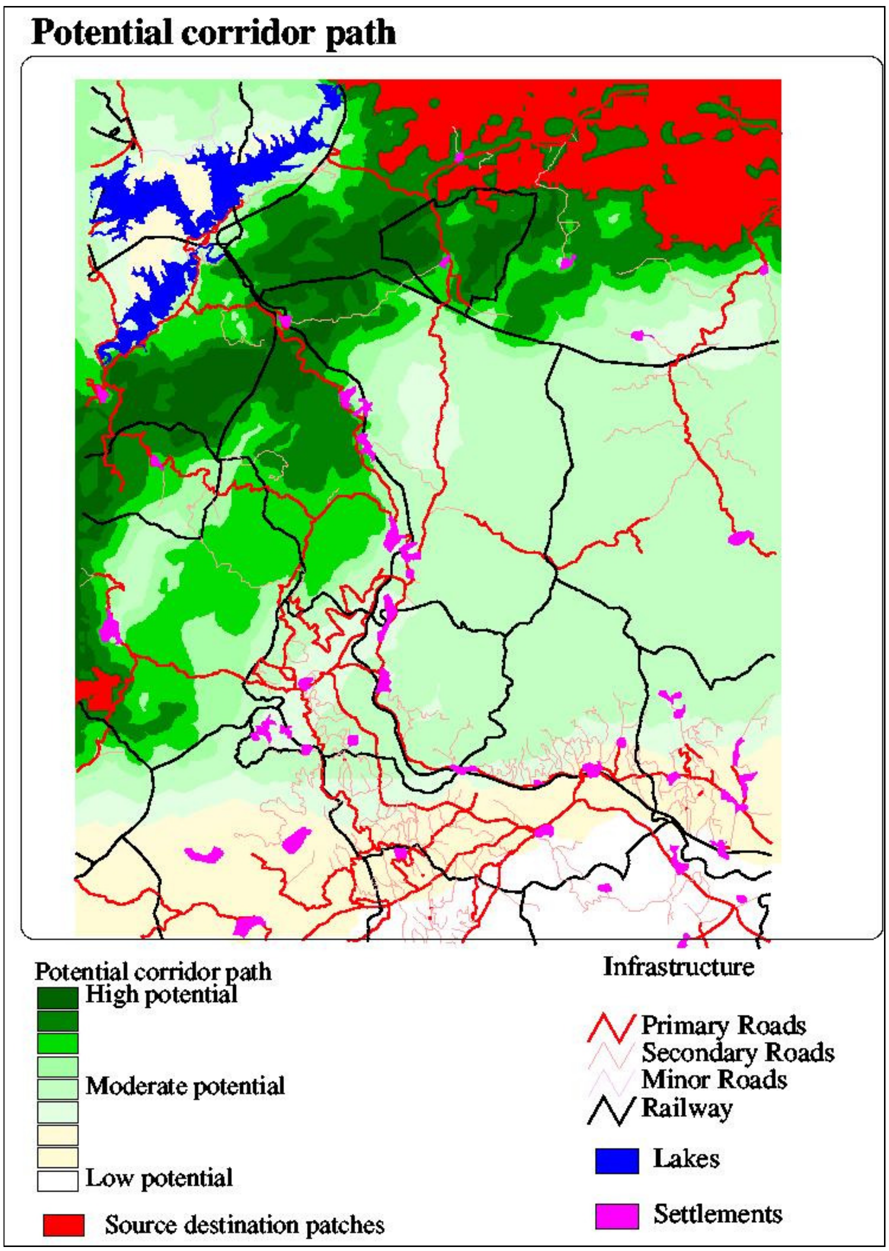

Figure 27. Potential corridor location across the study area

4.2.6 Potential corridor network within the study area

Connectivity in the landscape refers to the degree that all nodes in a system are connected by corridors. Alternative corridors or loops are important in minimising potential barriers to movements. When wide and internally diverse corridors are not possible, a network of corridors may collectively encompass a range of habitat types. Such network may preclude against any catastrophic event that could potentially destroy a single travel corridor (Fleury and Brown, 1997). Hence an approach to delineate a potential network was proposed and applied. Figure 28 shows the potential corridor network between the identified patches.

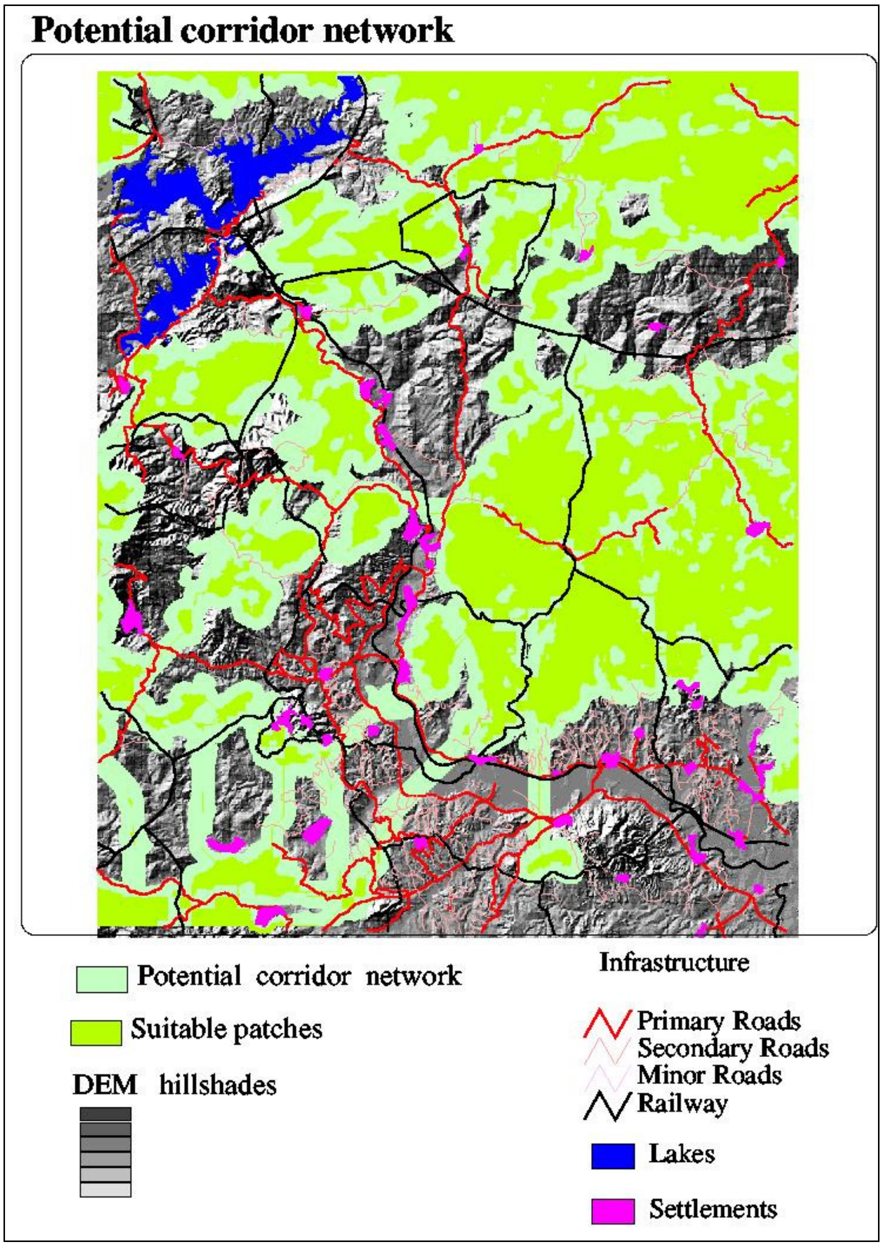

Figure 28. Potential corridor network locations

4.3 Discussion

The main objective of this study was achieved by identifying the general steps in corridor analysis and design (see section 3.3) and implementing them in a GIS environment. Nine steps were identified out of which the last two, evaluation of results and implementation, were beyond the scope of the thesis. Potential corridor locations were delineated and the results presented as maps and tables. An interactive GIS process model was developed with procedures to assist in meeting the goals of each identified step.

The first specific objective was to integrate habitat suitability model into GIS. The main aspect to be considered in corridor analysis is the suitability of landscape features with respect to species requirements. Hence, habitat mapping and evaluation is a prerequisite to the design of ecological corridors. To identify suitable wolf habitats, a statistical function to quantify habitat suitability for wolf was adapted and integrated in to GIS (ArcInfo GRID) using the mathematical map algebra functions. This simplified the process of mapping potential suitable wolf habitats and their visualisation within the study area of Alora. The habitat characteristics that influence the suitability were easily measured and quantified in the GIS environment. This included the amount in terms of percentage cover, size in terms of area and the location of each suitable habitat in relation to other suitable and un-suitable habitats.

The second objective was to identify suitable habitat patches that could be used for species re-introduction or be part of the wider ecological corridor network in the region. By applying classification rules, suitable patches were derived from the suitability map as those contiguous regions that satisfied the suitability level as dictated by the suitability function and the size in area. Further, the shape of a patch and the isolation based on weighted distance from other patches are important characteristic to be considered. The factors were derived for each identified patch and could be used in further analysis of patch suitability.

The third objective was to delineate potential connecting corridors between the identified habitat patches. This was achieved by making some assumption on animal dispersal behaviour, for GIS application. A GIS performs analysis on the basis of spatial location of objects, and the distances between the objects, hence, it was necessary to identify the problem in this respect. Potential corridor locations were identified by converting the habitat suitability of areas between patches (matrix) into weighted distances (resistance to dispersal by landscape). Routes of least resistance, which can be designated as corridors, were derived. This was achieved by using the "cost distance" analysis tools within ArcInfo GIS.

The final objective was to come up with a system that could generate different scenarios for application in a decision making process. This was achieved by making it possible for the user to adjust the parameters of corridor analysis within the developed process model. The adjustable parameters includes: scale of analysis, road-length weight factors, suitability and area threshold values, dispersal resistance weights, selection of source and destination patches and the reclassification processes for deriving the corridors. Performing the analysis using different window size, which controls the scale of analysis, was used as an example of adjusting the parameters.

The overall ability of GIS to map suitable habitats and corridor locations depends on the appropriateness and integrity of the ecological models used. In the complexity of the real world a number of different outcomes may be expected, as a result of variables not measured or considered. The results from GIS analysis need to be verified. The validation should involve experts in the related disciplines of ecology and landscape analysis. Characteristics of areas delineated as potential corridors should be studied in detail for proper evaluation of the GIS results. This was not possible due to lack of time.

The development of the process model has shown the important roles that both GIS and remote sensing play. Remote sensing is an important source of GIS data. Data can be captured easily and cost effectively. This is due to the fact that satellite images cover very large area, even those, which might not be accessible in the normal field work-studies. The availability of different types of Remote sensing data provides the user with a wide choice of information, to solve the specific problem. On the other hand, GIS has been used to organise the collected information into usable forms. This is by means of using GIS functionality as single commands or inform of macros. Overlay of maps has long been used to identify optimal locations in land use planning. The availability of GIS now makes the approach routine, as this is a core function in GIS analysis. The overlay process provides a means of comparing different locations based on the combination of existing characteristics within each location. This has made it easier to select, tabulate, classify, summarise and map information on the basis of spatial locations and in a format that can be easily understood by all in a decision making process. In the design, the GIS allowed the representation of complex spatial relations and structures, which are common in spatial problems. The GIS process model allows analysis of data at different scales. This is a major advantage when dealing with habitat evaluation, where most often the required scale is not known.

The integration of suitability statistical models and GIS has made it possible to delineate potential corridor locations in a mixed habitat with some advantages and limitations:

A major problem in GIS analysis is error propagation in each level of data capture and analysis. The sources of error are mainly positional due to inaccurate data entry (digitising), and data transformation (vector to raster and vice versa) resulting in loss of information. The aspect of data accuracy should be taken very seriously in the application of GIS to solve spatial problems. This may limit the accuracy and interpretation of a final overlay product. Main source of error for this analysis could be on the image classification. The classification results should be verified in the field.

The use of suitability models has reduced the subjectivity encountered in weighting the dispersal resistance of landscape features to species. This is of course dependent on the accuracy of the habitat model used. The development of a local habitat statistical function would have improved the reliability of the results generated. A major problem of using habitat models derived elsewhere is in aggregation of identified cover types to fit the model parameters. This was the case with the Lime/bare/rocky cover type. It was not clear whether to classify it in the same class as woody natural areas or herbaceous natural areas. Finally it was arbitrarily classified in the same category as herbaceous natural areas and assigned the same suitability-weighting factor.

The problem of subjectivity in assigning resistance was only partially solved in relation to the assumption of species preference to suitable habitats (see 3.5.4.1). Resistance for other transforming surfaces was assigned without much ecological evidence. Hence, more studies are required in this aspect for the GIS model application. The influence of transforming surfaces on dispersal is expected to be different among each surface, in this study they were all ranked on the same range of between 0 and 100. This could be a problem and some ecological evidence is required to be able to give weights among the transforming surfaces.

The potential corridor and the networks were delineated by reclassifying the accumulated cost surfaces to find connectivity. This was done through trial and error, as there are no specific guidelines on this aspect. Similarly there is no GIS functionality that could be used for delineation without the user subjectivity.

The analysis has mainly considered the physical properties of the region. One important aspect not taken into consideration was the availability of wolf prey (see section 2.6.3). This was not possible due to lack of accurate data on the distribution of local fauna e.g. ibex, which is a potential prey to the wolf.

In a study performed at local scale, the actual corridor routes are to be designed and implemented. The inclusion of local data sets related to social economic studies such as land ownership is important. This is more so in the management of a broad–ranging species such as the wolf in a mixed habitat. Landowners are the main stakeholders in a rural set up and in nature conservation in general. In the designing of the corridors, the sentiments of the owners should be taken into consideration. Such sentiments could be used in determining the dispersal resistance on different land locations. The main difficulty with social economic information is on how to integrate it in a spatial problem. The model has tried to sort this problem by making the assignment of resistance open-ended. Hence, new transforming surface could be added to the model related to different stakeholders such as land ownership data sets and some weighting protocol.

The GIS model developed in this study can be applied in Alora region to define the priority management areas for re-introduction of wolf in the wider region of Andalucia. This can be achieved by

1. Delineation of suitable habitat sites and connecting corridor locations which could be managed in a manner that will encourage species to use them during migration or dispersal.
2. Creation of different scenarios, which has been made easier in the model, by allowing the user to adjust some of the values of model parameters.
3. Viewing of potential land use changes (e.g. location of corridor) by the stakeholders thus seeing points of potential conflicts before the implementation of a particular measure e.g. protection level in a particular region, which might be in conflict with the interest of the stakeholders.

Many GIS process models for environmental analysis have been developed (Garcia and Armbruster; 1997; Walker and Craighead 1997; Swetnam et al. 1998) just to name a few. The aim of any GIS process model is to give the users, a tool that can assist in solving the problem at hand from start to the finish. The GIS model developed in this work allows the user to perform both habitat suitability mapping and analysis, and ecological corridor delineation in one process. In most cases the two are performed using separate processes. A number of models in the field are "black boxes" in which the user has no control over the running of the process. In this case the user has control over the process and is able to adjust the variables or even add new procedures within the developed process quite easily.

Three possible improvements of the GIS process model are suggested:

1. Integration of GIS and environmental models could be improved by including other aspects of habitat evaluation e.g. the development of the statistical function. This will make the whole process of habitat evaluation to be performed within the GIS environment, which has many advantages when dealing with spatial problems.
2. The data action programme (ArisFlow) can be improved by including proper menus for the adjustment of parameters related to the problem variables.
3. The developed model does not allow direct viewing of the graphics where one has to start ArcView separately to view the maps. This is possible with advanced programming, which was beyond the scope of this work

5 CONCLUSION

The principal objective of this study was to formalise the thinking steps in corridor design and transforming them into a GIS supported process. The main steps in corridor design were identified and programmed in the GIS. This was achieved by developing a processing model and procedures within a raster GIS environment. By applying habitat suitability model, suitable habitat patches were delineated. The delineation of potential corridor routes was achieved by using GIS distance analysis functions and the assignment of different landscape resistance on the basis of landscape suitability as species habitat. Three possible corridor scenarios have been produced mainly, the patch isolation, the possible corridor routes between two patches and a potential corridor network. Without GIS, this task would have been very difficulty.

The research has described many of the basic processes of a GIS and remote sensing in a logical sequence to solve complex spatial problem. A series of standard processes, such as satellite image processing and classification, reclassifying, overlaying, distance, and neighbourhood operations in GIS were used to subdivide the spatial problems into a series of primitive operations. The process model has been depicted with flowcharts and the actual command macros applied. The initial data layers are shown, followed by a standard process performed on the data layer, followed by an output created by the processing function performed. An output data layer then may be used as input to another process. Various inputs, processes, and outputs are diagrammed until the solution is derived. The process model provides the pathway for solving the specified spatial problem in a GIS environment.

The model is capable of dynamic simulations and provides spatial ''what if '' analysis especially in problems related to location selection. The ability to adjust the weights or the threshold values of problem factors can be used to simulate the attitude of various stakeholders in decision making process.

Another advantage of the process modelling approach is its flexibility. New considerations can be added easily or existing ones can be refined. The approach also provides an effective means for communicating the process used, including consideration of the specific application and fundamental procedures applied. A flowchart provides an excellent tool for communicating the logic, assumptions, and relationships used in the analysis.

The use of GIS provides a powerful tool for determining the size, location and distances of habitats on the landscape. The information, the analysis that accompany it, and the software that support it can be packaged as one of the tools of decision support system. To the ecologists and planners the GIS approach presented in this work is an example of how ecological and landscape information can be manipulated, packaged and presented in such system.

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APPENDICES

GIS MACRO programs used

APPENDIX 1

Macro for calculating land cover percentage using different window sizes

```
/* Program name: CALCOV.AML
/* This AML calculates the percentage cover of each land cover type
/* from a Landcover map. This is calculated as percentage of cells
/* within a given cover type within  %.varcell% by %.varcell% window

&args .landcov .lcovs .varcell

/* where .landcov is the land cover  file ; .lcovs is the cover type description file
/* .varcell is the grid size in number of cells.

/* Open the cover type description file (Lcovs below) and read the code and name
&s filen = [open %.lcovs% os -read]
&If %os% ne 0 &then &return 'File not opened']
&Else &type 'File opened successfully'

/* Read the description file
&s llin = [read %filen% rs]

/* Perform the cover calculations for all cover types in the cover file (lcovs)
&do &while %rs% ne 102
  &s code [unquote [substr %llin% 1 2]]
  &s cov [unquote [substr %llin% 4 7]]
  &type %cov% %code%

  setwindow 334438 4059216 364749 4096700

  &if [exist %cov% -grid] &then kill %cov% all
  %cov% = con ( %.landcov% eq %code%,1,0)

  &if [exist %cov%perc -grid] &then kill %cov%perc all
  &type Computing %cov%perc size %.varcell%
  %cov%perc = ( (focalsum ( %cov%, rectangle, %.varcell% , %.varcell% ) ) * 100) ~
  / ( %.varcell% * %.varcell% )

  &if [exist %cov% -grid] &then kill %cov% all

  &s llin = [read %filen% rs]
&end
&s cls [close %filen%]

&return
```

APPENDIX 2

Description file containing the codes and short names for land cover types

```
/* File LCOVS
/* This file is read by program calcov.aml for the cover codes and the cover names.
22 water
23 limeba
24 pine
25 cereal
26 olive
27 natveg
28 semiveg
29 citrus
30 settm
```

APPENDIX 3

Macro for generating road density

```
/* Program name: GENRT.AML
/* The aml generates a Grid of specified size
/* For calculating the density of roads in a given area.

/* Set the arguments to be used wti is the weights assigned to various categories of
roads.
&args .width .height .wt1 .wt2 .wt3 .wt4

/*  .width and .height is the fishnet width and height in map units
/*  .wti are the weights for primary, secondary , tracks and railway respectively

/* set the minimum and maximum x,y location in mapunits for grid generation
&s .x = 334000
&s .y = 4059000

/*  Calculate the number of rows and columns (nrow , ncol)
/* 38000 is the total length of the study area and 32000 is the total width
&s .nrow =  [round [calc 38000 / %.height%]]
&s .ncol =  [round [calc 32000 / %.width%]]
&if [exists kmgrid -cover] &then kill kmgrid all

/* Start the generate module and give the parameters
generate kmgrid
grid
%.x%,%.y%
%.x%,[calc %.y% + 1]
%.width%,%.height%
%.nrow%,%.ncol%
q
```

```
/* build the Grid
build kmgrid poly

&if [exists kmiden -cover] &then kill kmiden all
identity allinfra kmgrid kmiden line

additem kmgrid.pat kmgrid.pat length1 8 18 f 5
additem kmgrid.pat kmgrid.pat length2 8 18 f 5
additem kmgrid.pat kmgrid.pat length3 8 18 f 5
additem kmgrid.pat kmgrid.pat length4 8 18 f 5
additem kmgrid.pat kmgrid.pat length 8 18 f 5

/* Start INFO module and calculate the lengths of various road types within the grid.
&data arc info
arc
arc
COMP CALC
RUN CALC
CALC LENGTH = LENGTH1 * %.wt1%  + LENGTH2 * %.wt2% + LENGTH3 *
%.wt3% + LENGTH4 * %.wt4%
CALC LENGTH = ( LENGTH / ( %.WIDTH% * %.HEIGHT% )) * 1000
Q
STOP
&end
wrddens = polygrid (kmgrid , length)
&return

/* Program name: CALC  Calculates the lengths within INFO
 10000  PROGRAM SECTION ONE
 10001 FORM $NUM1,5,5,I
 10002 SEL KMGRID.PAT
 10003 CALC LENGTH = 0
 10004 CALC LENGTH1 = 0
 10005 CALC LENGTH2 = 0
 10006 CALC LENGTH3 = 0
 10007 CALC LENGTH4 = 0
 10008 CALC $NUM1 = $NOSEL
 10009 CALC $IDX5 = 2
 10010  SEL KMIDEN.AAT
 10011  RELATE 1 KMGRID.PAT $IDX5 LINK
 10012 DO WHILE $IDX5 LE $NUM1
 10013  REM DISPLAY $IDX5
 10014 RESELECT KMGRID-ID = $1KMGRID-ID
 10015 RUN CALC2 LINK
 10016 ASELECT
 10017 CALC $IDX5 = $IDX5 + 1
 10018 DOEND
 10019 SEL KMGRID.PAT
 20000 PROGRAM
 30000  PROGRAM END
```

```
/* Program name: CALC2 Run by Calc with link
10000  PROGRAM SECTION ONE
 10001 REM
 20000 PROGRAM
 20001 IF CLASS = 1
 20002  CALC $1LENGTH1 = $1LENGTH1 + LENGTH
 20003 ENDIF
 20004 IF CLASS = 2
 20005 CALC $1LENGTH2 = $1LENGTH2 + LENGTH
 20006 ENDIF
 20007 IF CLASS = 3
 20008 CALC $1LENGTH3 = $1LENGTH3 + LENGTH
 20009 ENDIF
 20010 IF CLASS = 777
 20011 CALC $1LENGTH4 = $1LENGTH4 + LENGTH
 20012 ENDIF
 30000  PROGRAM END
```

APPENDIX 4

Macro for generating suitability map

```
/* Create population density
Popgrd. = Con (settmperc. > 0,  (settmperc *  82  ) /  100   , 0 )

/* Program name: SUIT.AML
/* The following statements calculate the suitability index
/* based on the input parameters of vegetation cover , Human influence
/* and the human activity indicators of infrastructure density.

&args .water .limeba .pine .cereal .olive .natveg .semiveg .citrus ~
 .popgrd .roaddens .suit .elev
/* the args represent water,  lime/bare/rocky, pine, cereal, olive almond,
/* natural vegetation , seminatural, citrus , population density , roaddensity
/* percentage cover calculated in calcov.aml suit is the resulting grid and
/* elev is the elevation from DEM
setwindow %.water%
setcell %.water%
/* The suitability formula = 1 / 1+ e^^-(z)
/*
&if [exists %.suit% -grid] &then kill %.suit% all
&type Computing %.suit%
docell
  zgr := 1.1 - (4.19 * %.roaddens%) - (0.10 * %.popgrd%) + (0.07 * %.natveg%) ~
  + (0.02 * %.semiveg%) - (0.36 * %.pine%) ~
  - (0.36 * %.citrus% ) - ( 0.06 * %.cereal% ) ~
  + (0.02 * %.limeba% ) - (0.36 * %.olive% ) - (0.36 * %.water%) ~
```

```
  + ( 0.01 * %.elev% )
 zexp := exp(-1 * zgr)
 zplus := 1 + zexp
 %.suit% = 1 / zplus
end
&echo &off
&return
```

APPENDIX 5

Macro for creating separate grids of sources and destination patches

```
/* Program name: SOUDEST.AML
/* The program reads the source and destination patch ids and generates the necessary
/* grids for specific and network corridor analysis.

&args .sclust .ss1 .ss2
/* where .sclust is the input suitable cluster grid and .ss1 and ss2 are the identifiers
/* for source and destination grid.
&echo &on
grid
mape landcov
setwindow 334438 4059216 364749 4096700
setcell 15

/* Kill the old grids if they exist (set 1).
&if [exists dest1grd -grid] &then kill dest1grd all
&if [exists sos1grd -grid] &then kill sos1grd all

/* select the destination and source (set 1)
dest1grd = con(%.sclust% eq %.ss1%,%.sclust%)
sos1grd = con(%.sclust% ne %.ss1%,%.sclust%)
/* Kill the old grids if they exist (set 2).

&if [exists dest2grd -grid] &then kill dest2grd all
&if [exists sos2grd -grid] &then kill sos2grd all

/* select the destination and source (set 2)
dest2grd = con(%.sclust% eq %.ss2%,%.sclust%)
sos2grd = con(%.sclust% ne %.ss2%,%.sclust%)

&echo &off
&return
```

APPENDIX 6

Macro for assigning resistance values to landscape features

```
/* Program name: RESIST.AML
/* The following AML creates the cost surface
/* from the input grids of slope suitability settlements and water sources.

&args .slope .waterperc  .settmperc .suit
/* .slope grid for slope percentage, waterperc and settmperc are the water and
/*  settlement percentage cover and suit is the suitability grid

&echo &on
grid
mape landcov
setwindow 334438 4059216 364749 4096700
setcell 15

/* Create suitability cost surface
&if [exists costsuit -grid] &then kill costsuit all
costsuit = ( 1 - %.suit% ) * 100

/* Create slope cost surface
&if [exists costslope -grid] &then kill costslope all
costslope = con(%.slope% ge 60,%.slope%,0)

/* Create lakes costs surface
&if [exists costlake -grid] &then kill costlake all
costlake = con(%.waterperc% gt 0,100,0)

/* Create settlement  costs surface
&if [exists costsett -grid] &then kill costsett all
costsett = con(%.settmperc% gt 0,100,0)

/* Derive the final resistance surface by adding up
&if [exists costsurf -grid] &then kill costsurf all
costsurf = costsuit + costslope + costlake + costsett

&echo &off
&return
```

APPENDIX 7

Commands used for clustering analysis

```
Suitover = con (suit > 0.6 , 1 )
Suitrgn = regiongroup (suitover , # , EIGHT , WITHIN , # , NOLINK)
Suitperi = zonalperimeter (suitrgn)
Suitarea = zonalarea (suitrgn)
Suitavg = zonalmean (suitrgn , suit )
Indice = (Suitperi / ( 2 * sqrt(Suitarea * 3.14 )))
Avgarea = Suitarea * suitavg
Sclusters = con ( avgarea > ( 1000000 * 0.6 ) ,suitrgn  )
```

APPENDIX 8

Commands used in making corridor scenes

Isolation

```
Proxim = eucallocation (sclusters)
Meanprox =  int(zonalmean (proxim , clustdistance))
Clustdistance = costdistance(sclusters, ( Costsurf / 100 ))
```

Corridor A-B

```
Costaccum1 = costdistance (dest1grd, ( Costsurf / 100 ) , cost1bkln)
Costaccum2 = costdistance (dest2grd, ( Costsurf / 100 ) , cost2bkln)
Corridpath = corridor (costaccum1, costaccum2)
```

Corridor Network

```
Tmp1 = costpath( sos1grd, costaccum1, cost1bkln) : costpath1 = float (tmp1.pathcost)
: kill tmp1
Tmp2 = costpath( sos2grd ,costaccum2, cost2bkln) : costpath2 = float( tmp2.pathcost)
: kill tmp2
Leastpaths = con( isnull(costpath1) , costpath2, costpath1)
Accumpaths = costdistance( leastpaths , Costsurf)
```

APPENDIX 9

The GIS model was developed on a Digital UNIX version 4.0 a machine (128 Mb Ram). A minimum of 500 Mega bytes was required to successively run the model for this particular study area.

Arisflow data action flow chart programme: