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GIS-BASED CUMULATIVE EFFECTS ASSESSMENT

**Brian Blaser, Hong Liu, Dennis McDermott, Fred Nuszdorfer,
Nguyet Thi Phan, Ulziisaikhan Vanchindorj,
Lynn Johnson, and John Wyckoff**

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16. Abstract

This report was prepared as part of a research project conducted for the Colorado Department of Transportation (CDOT) over a 2-year period. It describes the development and application of geographic information systems (GIS) and remote sensing (RS) databases and analysis models for cumulative effects assessment resulting from growth associated with transportation infrastructure. A spatial environmental database was collated from various sources for a 53 km by 97 km (33 mi. by 60 mi.) region bounding I-25 from Denver to near the Colorado-Wyoming border.

This report demonstrates several ways that GIS can be used as a tool for performing Cumulative Effects Assessments (CEA). It presents four environmental assessments which use GIS. The first two, a habitat suitability study and a land use change analysis, demonstrate commonly used GIS overlay and distance techniques; the remaining two use less common and more complex technologies. The third study links a spatial database with commonly used flood design procedures to measure hydrologic impacts due to land use change. The final study uses a number of techniques for development growth modeling. Specific applications for CEA are given in the land use and hydrologic studies.

Development of these data sets in standardized formats, scales, and projections provides a means for comparison of attributes across the study region or at any given location. Ultimately, the GIS data would be implemented as compatible with the CDOT transportation geodatabase currently under development, thus making a seamless interface for CDOT staff and contractors to access all data for the region in support of planning activities. CDOT may use these data and techniques for transportation planning and developing NEPA documents, or make them available to stakeholders and interested Departments of Transportation across the nation.

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Overall, the sharing of data and opinions by all involved speaks to the high level of professionalism evident in the ranks of the GIS and environmental planning work force, all of whom provide the foundation for maintaining and enhancing our environmental resources in the face of increased pressure of population growth and urban development.

EXECUTIVE SUMMARY

This report was prepared as part of a research project conducted for the Colorado Department of Transportation (CDOT). The project, entitled “GIS-Based Cumulative Effects Assessment” (Study No: 34.65) has been conducted by the University of Colorado Geographic Information Systems Programs’ faculty and staff over a 2-year period, from April 2002 through March 2004. The report describes the development and application of geographic information systems (GIS) and remote sensing (RS) databases and analysis models for cumulative effects assessment resulting from growth associated with transportation infrastructure. A spatial environmental database was collated from various sources for a 53 km by 97 km (33 mi. by 60 mi.) region bounding I-25 from Denver to near the Colorado-Wyoming border.

This report demonstrates several ways that GIS can be used as a tool for performing Cumulative Effects Assessments (CEA). It presents four environmental assessments which use GIS. The first two, a habitat suitability study and a land use change analysis, demonstrate commonly used GIS overlay and distance techniques; the remaining two use less common and more complex technologies. The third study links a spatial database with commonly used flood design procedures to measure hydrologic impacts due to land use change. The final study uses a number of techniques for growth modeling. Specific applications for CEA are given in the land use and hydrologic studies.

Development of these data sets in standardized formats, scales, and projections provides a means for comparison of attributes across the study region or at any given location. Ultimately, the GIS data would be implemented as compatible with the CDOT transportation geodatabase currently under development, thus making a seamless interface for CDOT staff and contractors to access all data for the region in support of planning activities. CDOT may use these data and techniques for transportation planning and developing NEPA documents, or make them available to stakeholders and interested Departments of Transportation across the nation.

Implementation Statement

The techniques demonstrated in this study include procedures for 1) developing regional spatial data into a coordinated GIS database, 2) characterizing and identifying wildlife habitat, 3) quantifying and assessing land use change, 4) integrating commonly used hydrologic modeling procedures with a spatial database for assessing changes in flood flows due to changes in land use, 5) developing a growth model to predict the likely areas of future growth, and 6) demonstrating the application of these GIS and modeling methods for assessing cumulative environmental effects associated with transportation projects. Development of these data sets in standardized formats, scales, and projections provides a means for comparison of attributes across the study region or at any given location. Ultimately, the GIS data would be implemented as compatible with the CDOT transportation geodatabase currently under development, thus making the data and models available for CDOT staff and contractors to use for the region in support of planning activities. CDOT may use these data and techniques for transportation planning and developing NEPA documents, and make them available to stakeholders and interested Departments of Transportation across the nation.

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1.0 INTRODUCTION

1.1 Overview

The Colorado Department of Transportation conducts evaluations of environmental impacts, including Cumulative Effects Assessment (CEA), as required under the National Environmental Policy Act (NEPA), and seeks to develop quantitative and repeatable procedures for assessing cumulative effects to support planning and better decision-making. Geographic Information Systems (GIS) and remote sensing are geospatial technologies that have proven their value in many different forms of environmental assessment. The Council on Environmental Quality (1997) recognized their potential value in cumulative environmental effects assessment. Data in the form of satellite imagery and aerial photography can provide a means of evaluating significant resources over the time frames appropriate for CEA. GIS also makes it possible to manipulate enormous amounts of data and it provides a mechanism for continuously updating changes in resource distribution and character, an important aspect of the iterative nature of CEA. The ability to manipulate spatial data also provides the environmental analyst with a mechanism for examining alternate action scenarios and to forecast the sustainability of the environment in response to land use changes commonly associated with the proposed transportation projects.

1.2 Objectives

The objectives of this project are to demonstrate some of the ways GIS can be used to facilitate Cumulative Effects Assessments and provide a number of examples of its use to analyze wildlife habitat, land use, hydrology, and development growth which can then be used to assess the environmental effects of transportation projects. The project incorporates satellite imagery, aerial photography, and other data into a coordinated spatial database, then demonstrates a number of innovative GIS techniques for habitat characterization and land use analyses. The use of more sophisticated hydrologic modeling analyses to assess the impacts of urbanization on flood flows is illustrated. In combination with CDOT transportation project data, these techniques can be used to create quantifiable and repeatable processes for formal cumulative effects analyses.

2.0 CUMULATIVE EFFECTS ASSESSMENT OVERVIEW

2.1 Introduction

Over the past decade environmental analysis professionals have increasingly embraced the idea that in order to fully assess the impacts of a project on the environment a holistic approach is needed which can assess the additive and interactive responses to both single and multiple actions across time and geography. The Council on Environmental Quality (CEQ) developed formal Cumulative Effects Assessment guidelines in response to provisions in the National Environmental Policy Act of 1969 and the reality that very few impact studies considered, in detail, the many possible effects associated with any particular action or project (1997). The CEQ defined CEA as:

> The impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (Federal or non-Federal) or person undertakes such other actions (40 CFR § 1508.7)

Further, the Council developed an analytical framework in its document "Considering Cumulative Effects Under the National Environmental Policy Act" which established guidelines for organizations wishing to complete either Environmental Impact Statement or Environmental Assessment documents. These guidelines walk analysts and decision-makers through a process that broadens the analytical scope both spatially and temporally, and considers a much wider field of potential impacts that could result from a proposed project both when considered in isolation and when combined with the effects of the projects of other actors. The CEQ handbook provides guidelines for assessing potential effects to specific resources, ecosystems, and human communities, with the aim of developing appropriate mitigation and monitoring of future conditions. GIS and RS techniques enable an analyst to do a variety of tasks which were previously quite difficult and time-consuming, such as assessing historical change and alternative actions. The goal is to identify all the relevant impacts from a proposed project and make good decisions based on comprehensive information.

2.2 Geographic Information Systems

Geographic information systems are computerized systems that are used to store and manipulate geographic information (Figure 1). There has been a convergence of GIS with the technologies for surveying, RS, photogrammetry, Global Positioning System (GPS), computing and communication. A GIS includes technologies for data capture that include engineering measurement devices that record readings in digital formats and can be ported directly into a GIS spatial database (e.g., GPS). Data capture technologies include as well remote sensing by satellites and airborne platforms. Satellite imagery of the land is received in various wavelengths so that particular aspects of the land surface can be characterized through image processing procedures. Aerial imagery is most often of the photographic type, particularly for development of high-resolution topographic maps of urban areas and identification of urban features.

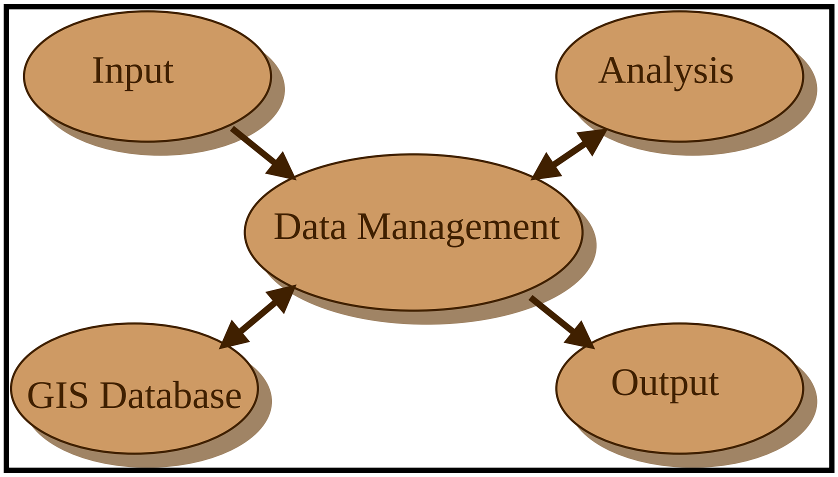


Figure 1. Component view of a GIS

Regardless of the source, there is a requirement that spatial data be identified in some coordinate reference system. GIS data storage technologies incorporate two distinct branches, the spatial database and the associated attribute database. Many GIS software maintain this distinction, the spatial data is characterized as point, lines and polygons. Other GIS spatial data are handled as images, or rasters, having simple row and column formats. Attribute data are handled in relational database software comprised of records and fields, and the power of the relational model is applied for these data.

A GIS provides specialized analysis capabilities specifically keyed to the spatial realm and not generally available elsewhere. An analysis function unique to GIS is the overlay operation whereby multiple data themes can be overlain and the incidence of line and polygon intersections are derived. This graphical and logical procedure is used in many ways to identify the correspondence between multiple data layers. Other GIS functions include networks and connectivity operations, terrain analyses, statistical interpolation and other neighborhood procedures, as well as functions for spatial database development and maintenance.

2.3 Components of Cumulative Effects Analysis

The traditional components of an Environmental Impact Assessment (EIA) include 1) project scoping, 2) describing the affected environment, and 3) determining the environmental consequences. In CEA these components have been expanded to consider change over time, relevant projects of other organizations that currently exist or will exist in the future, all targets which may be affected by the project, and the ability of resources to adapt to new conditions. The following list summarizes CEA’s guiding principles.

1. Include past, present, and future actions.
2. Include all federal, nonfederal, and private actions.
3. Focus on each affected resource, ecosystem, and human community.
4. Focus on truly meaningful effects.
5. Use natural boundaries.
6. Address additive, countervailing, and synergistic effects.
7. Look beyond the life of the action.
8. Address the sustainability of resources, ecosystems, and human communities.

Examples of cumulative effects include time crowding, time lags, space crowding, cross boundary (when effects occur away from the source), fragmentation, compounding from multiple sources or pathways, indirect or secondary effects, and fundamental changes in system behavior or structure because of triggers or crossing sustainability thresholds (p.9).

Based on these principles, the steps listed in Table 1 have been developed by the CEQ as appropriate for completing a CEA.

Table 1. CEA steps associated with EIA components

EIA Components	CEA Steps
Scoping	1. Identify the significant cumulative effects issues associated with the proposed action and define the assessment goals. 2. Establish the geographic scope for the analysis. 3. Establish the time frame for the analysis. 4. Identify other actions affecting the resources, ecosystems, and human communities of concern.
Describing the Affected Environment	5. Characterize the resources, ecosystems, and human communities identified in scoping in terms of their response to change and capacity to withstand stresses. 6. Characterize the stresses affecting these resources, ecosystems, and human communities and their relation to regulatory thresholds. 7. Define a baseline condition for the resources, ecosystems, and human communities.
Determining the Environmental Consequences	8. Identify the important cause-and-effect relationships between human activities and resources, ecosystems, and human communities. 9. Determine the magnitude and significance of cumulative effects. 10. Modify or add alternatives to avoid, minimize, or mitigate significant cumulative effects. 11. Monitor the cumulative effects of the selected alternative and adapt management.

For additional in-depth discussion of these guidelines, please refer to “Considering Cumulative Effects under the National Environmental Policy Act”, Council on Environmental Quality, 1997.

2.4 Appropriate Use of GIS for CEA

GIS maps should not be considered the final result of an analysis; they can be linked to analysis models in a comprehensive scientific and policy analysis. In addition, although the CEQ has established guidelines for CEA, no truly standard format or application of GIS tools exists. Keeping this in mind, the appropriate GIS actions associated with each step in the CEA process have been listed in Table 2. This is not an exhaustive list.

Table 2. GIS activities associated with CEA steps

CEA Steps	GIS Activities
1. Identify the significant cumulative effects issues associated with the proposed action and define the assessment goals.	Identify which variables have available data which can be used in a GIS, including metadata.
2. Establish the geographic scope for the analysis.	Collect data for all relevant impact areas, recognizing that the impact zones may be different for different resources (ex. water, air, and land)
3. Establish the time frame for the analysis.	GIS data which are available for the past and present provide the means to track historical changes, and forecasts of possible future conditions.
4. Identify other actions affecting the resources, ecosystems, and human communities of concern.	Create overlays to depict the area of proposed action and identify impact zones, including effects from non-project actions. Create maps aggregating all relevant activities.
5. Characterize the resources, ecosystems, and human communities identified in scoping in terms of their response to change and capacity to withstand stresses.	Use historical and remote sensing data sources to assess past resource responses to stresses.
6. Define a baseline condition for the resources, ecosystems, and human communities.	Create a list of resources within the study area. Collect or create individual data layers for each variable to be analyzed for a particular point in time.
7. Characterize the stresses affecting these resources, ecosystems, and human communities and their relation to regulatory thresholds.	Develop cause-effect spatial models of the stresses using GIS intrinsic functions and other procedures linked to the spatial data.
8. Identify the important cause-and-effect relationships between human activities and resources, ecosystems, and human communities.	Create overlays such as Habitat Suitability Indices (HSI) or analyze historical trends to predict future impacts.
9. Determine the magnitude and significance of cumulative effects.	Perform map overlays to determine aggregated impact levels. Compute spatial statistics of effects and compare with thresholds of significance.
10. Modify or add alternatives to avoid, minimize, or mitigate significant cumulative effects.	Perform regional analyses for all actions, including no-action through use of overlays, GIS functions, and computer simulation as appropriate.
11. Monitor the cumulative effects of the selected alternative and adapt management	Perform periodic time-series analysis for comparison to baseline status.

2.5 Benefits and Limitations of Using GIS to Perform CEA

GIS is a very powerful and useful tool and can be very efficient and effective for Cumulative Effects Analysis. The following is a partial list of appropriate uses:

- Establishing baseline conditions and study boundaries for regional assessment.
- Consolidating a large amount of data on different features (ex. soils, habitat, development, water, vegetation, wildlife habitat) to a common format and scale.
- Assessing physical/biological/human impacts.
- Performing periodic data updates.
- Creating quantitative and repeatable analyses.
- Providing inputs and links to other analytical methods.
- Using a wide variety of remote sensing data.
- Performing analyses at a variety of map scales.
- Developing standard rating systems for comparing disparate layers.
- Calculating additive effects.
- Identifying and quantifying fragmentation.
- Measuring change over time (past, present, future, or other time intervals).
- Identifying locations where certain conditions of interest occur.
- Identifying locations where impacts are greatest or least.
- Identifying locations that are impacted from multiple actions or projects.
- Viewing non-physical features (ex. political, zoning, or habitat boundaries).
- Forecasting future conditions.
- Performing iterative and/or “what if” analyses.
- Performing complicated mathematical algorithms when desired (ex. growth modeling).
- Providing excellent visual representation.

However, the use of GIS is not a substitute for in-depth, careful, and well-thought-out analysis and has a number of limitations:

- Requires good computing power, specialized software and occasionally hardware.
- Requires skilled, technical staff.
- Is often time-consuming.
- Can be expensive.
- Projections often differ from actual results; model calibrations are required.
- Is limited to effects based on location.
- Does not explicitly address indirect effects.
- Is prone to being interpreted as fact, while visual representations are often best guesses.

3.0 THE STUDIES

3.1 Introduction

The studies in this report were designed to be illustrative examples of some of the ways in which GIS can be used to facilitate a Cumulative Effects Analysis. Four components are discussed here. Each of these is fully discussed in the Supplemental Reports, and is summarized in this report along with a discussion of the final CEA. They are briefly summarized below:

Habitat Suitability Index (HSI). This series of models combines a variety of overlays containing information on environmental conditions such as vegetation, roads, development, water, and soils to rate habitat suitability within the study area for 5 threatened or sensitive species of birds and animals.

Land Use Change. A multi-criteria evaluation method (MCE) uses overlays to develop an Index of Development Attractiveness (IDA) model which predicts which areas are likely to experience growth based on a variety of inputs. The study also examined a new computational approach for the so-called Cellular-Automata simulator for growth and land use change

Cumulative Effects Assessment. A GIS-based CEA procedure was demonstrated by overlaying high growth potential areas with the HSI data to identify areas where growth is likely and where high-value wildlife habitat is potentially at risk.

Hydrology. This model translates a commonly accepted hydrologic procedure called the TR-55 computer model into a GIS format to assess the hydrologic impact on flood flows resulting from changes to land use over time.

3.2 The Study Area

The project area is the so-called I-25 northern corridor from Denver to Ft. Collins (Figure 2) having a total area of approximately 5141 sq. km (53 km by 97 km or 33 mi. by 60 mi.). The rationale for selection of the project area was primarily to support transportation planning activities for capacity expansion of the I-25 North corridor.

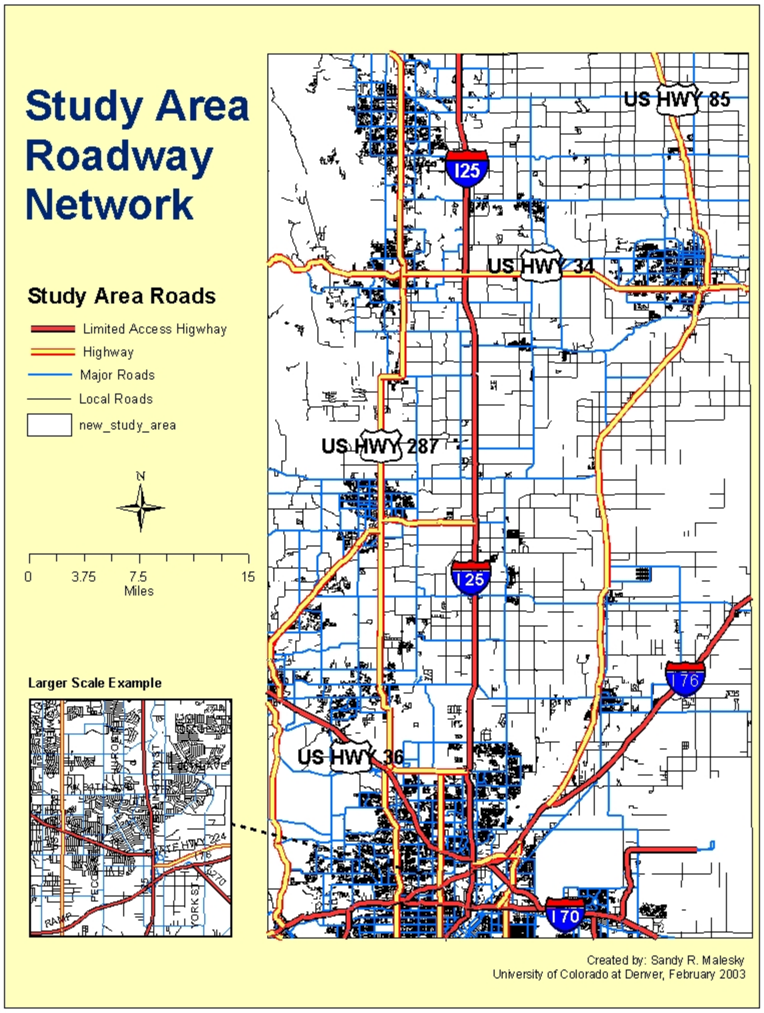


Figure 2. Project location

4.0 DEVELOPING A HABITAT SUITABILITY INDEX (HSI)

4.1 Introduction

In any environmental assessment, measuring impacts to wildlife is a very important component. An effort was made to categorize land within the study area based on its habitat suitability for 5 species: black-tailed prairie dog, Preble's meadow jumping mouse, ferruginous hawk, bald eagle, and American white pelican. Each of these species is to some extent affected by the urban land conversion and fragmentation of habitat. These species were selected because they are classified by state and federal government agencies as threatened, sensitive, or species of special concern.

The following project tasks were involved: 1) spatial database development, including satellite image and other data processing, 2) environmental factors and habitat suitability mapping, 3) growth modeling to identify lands having high development potential and 4) GIS-based procedures for environmental effects assessments.

4.2 Spatial Database Development

The GIS data came from a variety of sources. Every effort was made to identify and obtain relevant GIS and related data from the CDOT and other sources, such as federal agencies (e.g., Bureau of Land Management), other Colorado State agencies, and local government entities. Local data was often hard to obtain for the whole region as counties and municipalities have varying GIS capacities. All data relevant to the project have been collated and archived into a coherent database for easy retrieval. All GIS data were developed per CDOT standards (CDOT, 2001). In total, more than 50 data themes were obtained or developed for the study region, including topography, vegetation, soils, hydrography, jurisdictions, and transportation networks.

To assist in keeping track of the large number of raw spatial data sets, a cumulative effects data inventory dictionary (CEDID) was developed. The CEDID is a Microsoft® Access® database that provides an easily usable and centralized method of managing the metadata for the various coverages. Once a data set has been processed to the standard format and datum the metadata is formally established within the GIS database.

The following remotely sensed data was obtained from a variety of sources:

- **Vegetation maps** were obtained through a project conducted by the Bureau of Land Management (BLM), the Colorado Division of Wildlife (CDOW), and the Colorado Vegetation Classification Project (CVCP). The CVCP utilized Landsat Thematic Mapper data from the spring and fall of 1993-95. Image processing was performed at the National Applied Resource Sciences Center Remote Sensing Lab at the BLM, Federal Center in Denver, using ERDAS® IMAGINE® 8.2/8.3 and ArcInfo® software. Figure 3 is an example of the vegetation map data.

- **Land cover** type categories are based on a modified Anderson Land Use and Land Cover Classification System (1977). The original vegetation maps developed by the BLM and CDOW had been broken into subsets of individual watersheds and therefore had to be mosaiced and clipped to the I-25 corridor study area. The habitat suitability modeling work described below requires high quality vegetation mapping and this was provided by the CVCP.

4.3 Habitat Suitability Mapping

Habitat for key indicator species and ecosystems was characterized using a habitat suitability index (HSI) approach which maps the suitability of lands for habitat and environmental value. A habitat value map can be used in conjunction with growth models to assess cumulative environmental impacts over time in response to alternate transportation plans. HSI mapping builds on research from a number of other studies including the Habitat Evaluations Procedure, a widely used habitat assessment methodology which was developed by the U.S. Fish and Wildlife Service (USFWS, 1976). It requires the development of habitat suitability indices for individual species. Factors such as land slope, soil type, and nearness to riparian areas were considered.

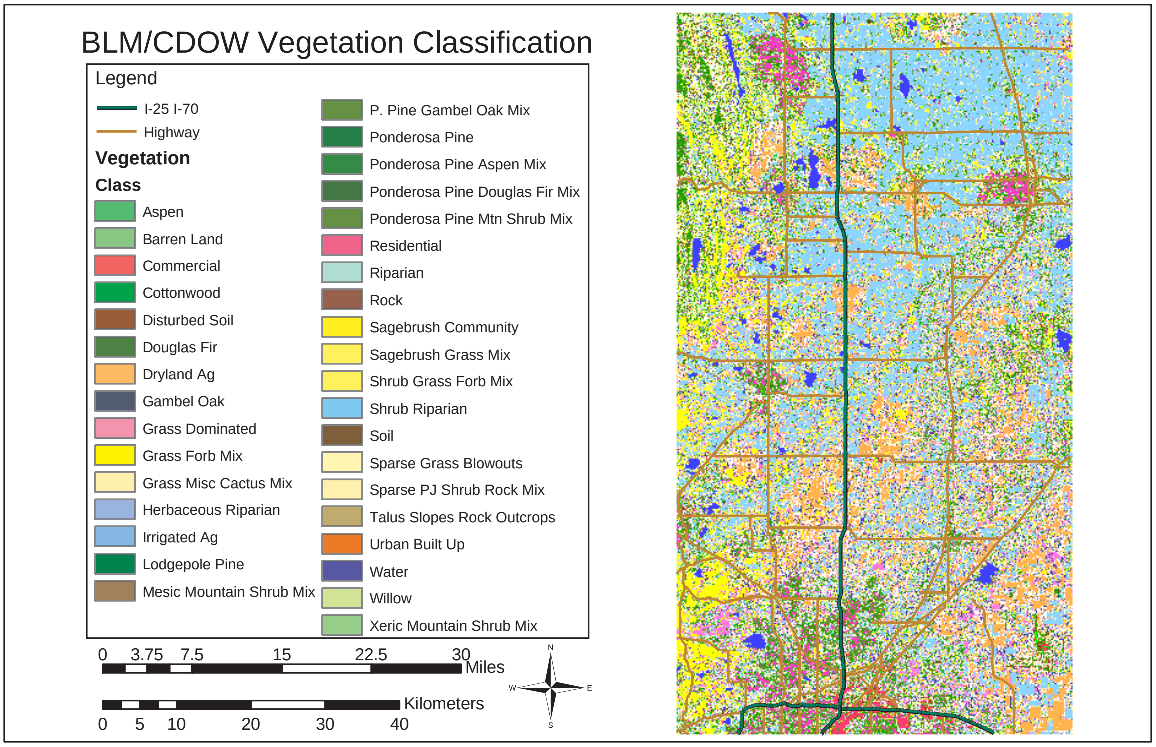


Figure 3. Vegetation map developed by Bureau of Land Management and Colorado Division of Wildlife

Although analysis was done on all 5 species in the Supplemental Report, for this illustrative discussion we will focus only on the black-tailed prairie dog (*Cynomys ludovicianus)*. This species was once the most common mammal species found in the Great Plains region of central North America (Hoogland, 1995), and in Colorado they occupied most of the native grassland areas of the eastern part of the state. Agriculture and other infrastructure growth factors have reduced the habitat of the prairie dog to fragmented remnants scattered throughout the region, but there are a number of pressures that effect their survival. They are considered to be pest species, transmitters of disease, and obstacles to development; their colonies are frequently poisoned as a result. For these reasons, CDOT considers CEA essential for this species. The HSI model for the prairie dog was developed using the procedures described above. The schematic in Figure 4 illustrates how the weighted themes were used in the analysis. Figure 5 is a grid generated by the model showing the distribution of suitable prairie dog habitat in the study area.

4.4 Using a Weighted Overlay Technique

Weighted overlay is a technique for applying a common scale of values to diverse and dissimilar inputs in order to create an integrated analysis (Environmental Systems Research Institute, 2000). The steps are enumerated below:

1. A numeric evaluation scale is chosen. This may be 1 to 10 or any other scale.
2. The cell values for each input theme in the analysis are assigned values from the evaluation scale and reclassified to these values. This makes it possible to perform arithmetic operations on grids that originally held dissimilar types of values.
3. Each input theme is weighted (i.e. assigned a percentage influence based on its importance to the model).
4. The total influence for all themes equals 100 percent.
5. The cell values of each input theme are multiplied by the theme's weight.
6. The resulting cell values are added to produce the output grid theme.

ESRI's ArcView® Model Builder® was used for this weighted overlay approach.

As you can see in Figure 4, a number of factors had to be carefully considered. Each input was evaluated for prairie dog suitability. For example, prairie dogs tend to avoid steeper slopes so these areas were given a lower rating than those with gentle, or no slope. Grasslands were a preferred habitat and were rated high. This process was repeated for all categories in each map.

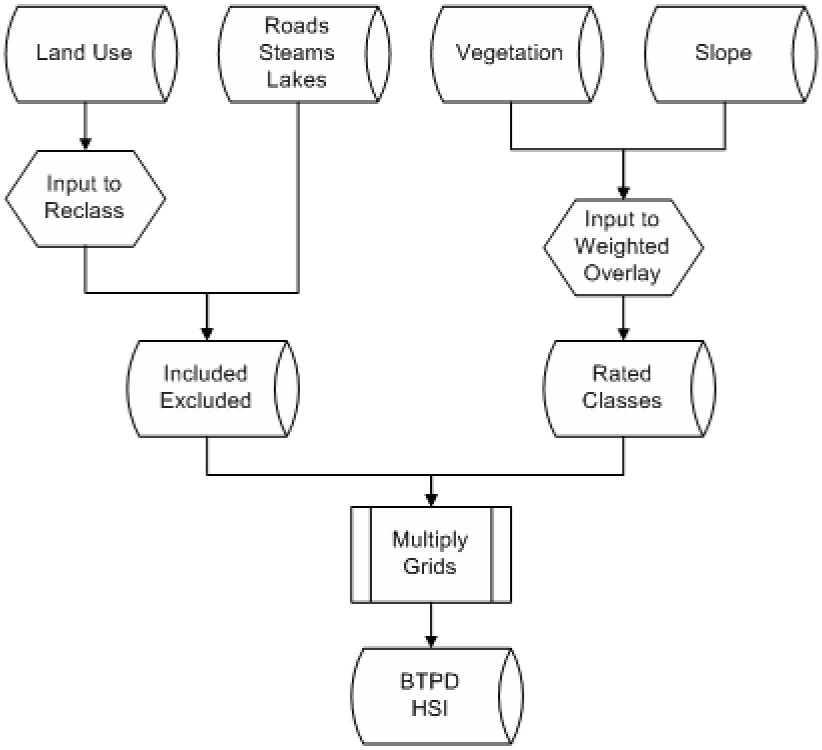


Figure 4. Habitat suitability index (HSI) model for prairie dogs

Once the overlays were completed, those areas with the highest overall habitat suitability were identified and can be seen in red. In contrast, the deepest green represents areas where we would not expect to find any prairie dogs.

The overlay techniques demonstrated in this study are readily accomplished in GIS. Combining layers, categorizing data within the layers, and manipulating the maps to identify an area of interest is a very powerful and easy manipulation of spatial databases.

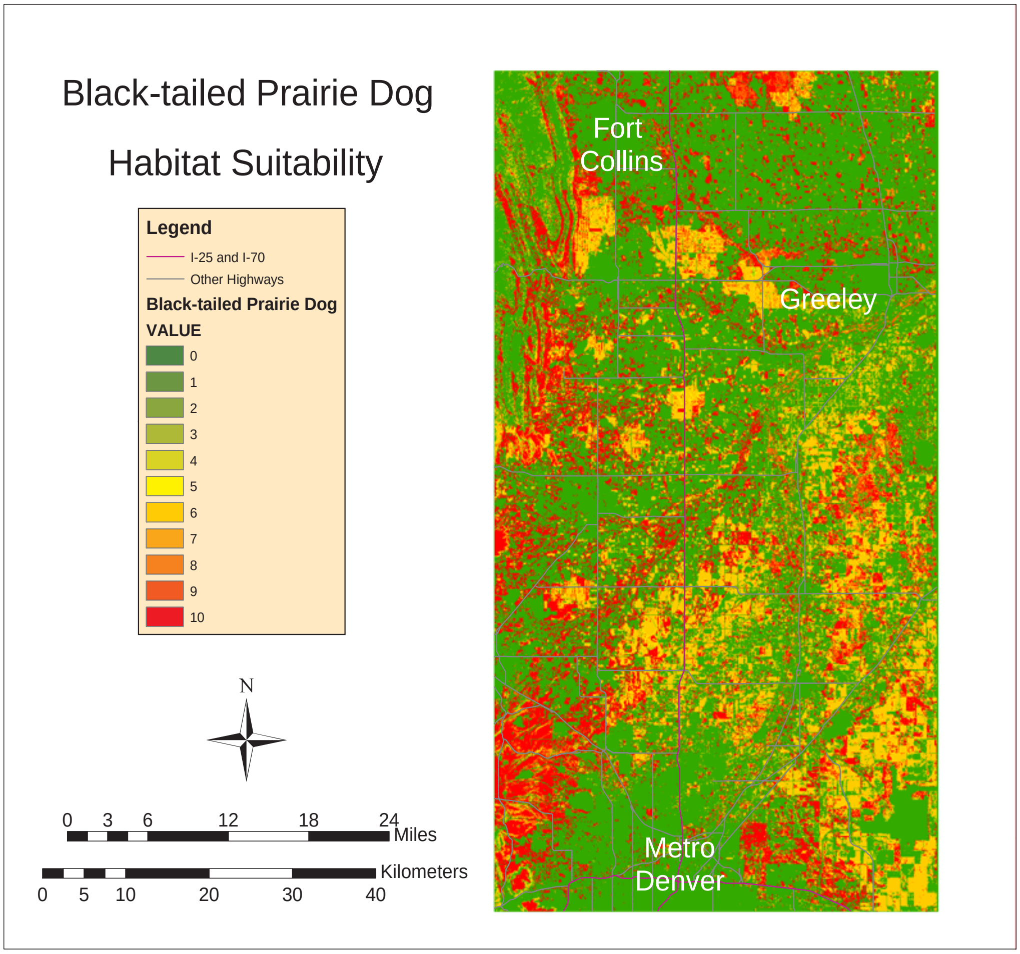


Figure 5. Habitat suitability index for the black-tailed prairie dog

5.0 LAND USE CHANGE MODELING

5.1 Introduction

A variety of methods have been developed to analyze land use and land use change over time. Spatially explicit models focus on (1) the *rate of change* between two or more classes, (2) the *location of change* in one or more classes, or (3) the *rate and location of change* between two or more classes. All of the methods collate spatial data at different points in time so that changes can be identified and quantified. The level of detail of the data is an important factor to consider. For example, coarser forecasts are usually acceptable for regional-scale analyses and smaller scale data is acceptable. The opposite is also true. In contrast to models that focus only on physical conditions, some models attempt to represent market factors of land demand and pricing, and the influence of land management strategies.

This study focused on two methods: 1) a Multi-Criteria Evaluation (MCE) approach, also known as cartographic, overlay, or suitability models; and a 2) Cellular Automata (CA) model.

5.2 Index of Development Attractiveness (IDA)

One component in developing analysis models for CEA is to be able to model the growth that occurs over time over an area. The goal is to develop an Index of Development Attractiveness (IDA) to identify areas where human development is most likely to occur. As transportation is an important component for development, any CEA will need to be able to predict where any such development will occur as the result of improvements to the transportation network. In a manner similar to how the Habitat Suitability Index was developed, in this case factors which are believed to be related to land use change are first derived (e.g., distance to roadways, slope) and then normalized to a common scale (e.g. 1 – 10). Each of these factor maps are multiplied by importance weights and then combined by addition to identify sites that have high composite suitability value in the study area. Land use at time *t* is assigned to those cells that are most suitable. The MCE approach is simple to apply, can combine factors based on different distributions (i.e. it does not assume that all factors have a linear relationship to change), and can accommodate updates. Unfortunately, there are no clear guidelines about which factors to include as inputs, or how to weight them. (This was also true in the HSI study.) Since the goal of this study is to measure and forecast change over time, calibration of the IDA model was attempted using historical data for 1977 and 1997. The calibration results provide insight into the accuracy of the IDA growth predictions.

Land use models have often focused on accessibility to nodes of employment, primarily the Central Business District (CBD). While the journey to work clearly influences location choice, access to other services and facilities including schools, shops, and public transport is also important. These are accounted for by classes calculated by the GIS such as "*Distance to Central Business District,*" "*Distance to Major Road Networks,*" and others.

The goal here was to develop an index based on a number of input themes that are weighted according to their perceived importance to the model. Each input theme (which may have multiple feature categories) was given a value between the numbers of 1 to 10 (1 being the least desirable and 10 the most desirable). Each input cell was multiplied by the weight assigned to that input theme. The cells from each input were then added together. Based on research, the IDA was computed based on factors for a) distance to major roads, b) distance to residential development, c) distance to central business district(s), d) slope and e) a variety of others. Areas with constraints on development (e.g., wetlands, reserved open space, flood plains) were excluded from development in the model. Other areas have been declared off limits for development for political reasons. Distance to major roads is an important factor contributing to development attractiveness. The schematic in Figure 6 shows how the analysis progressed. It should be noted that not all inputs need to be used to directly generate an index.

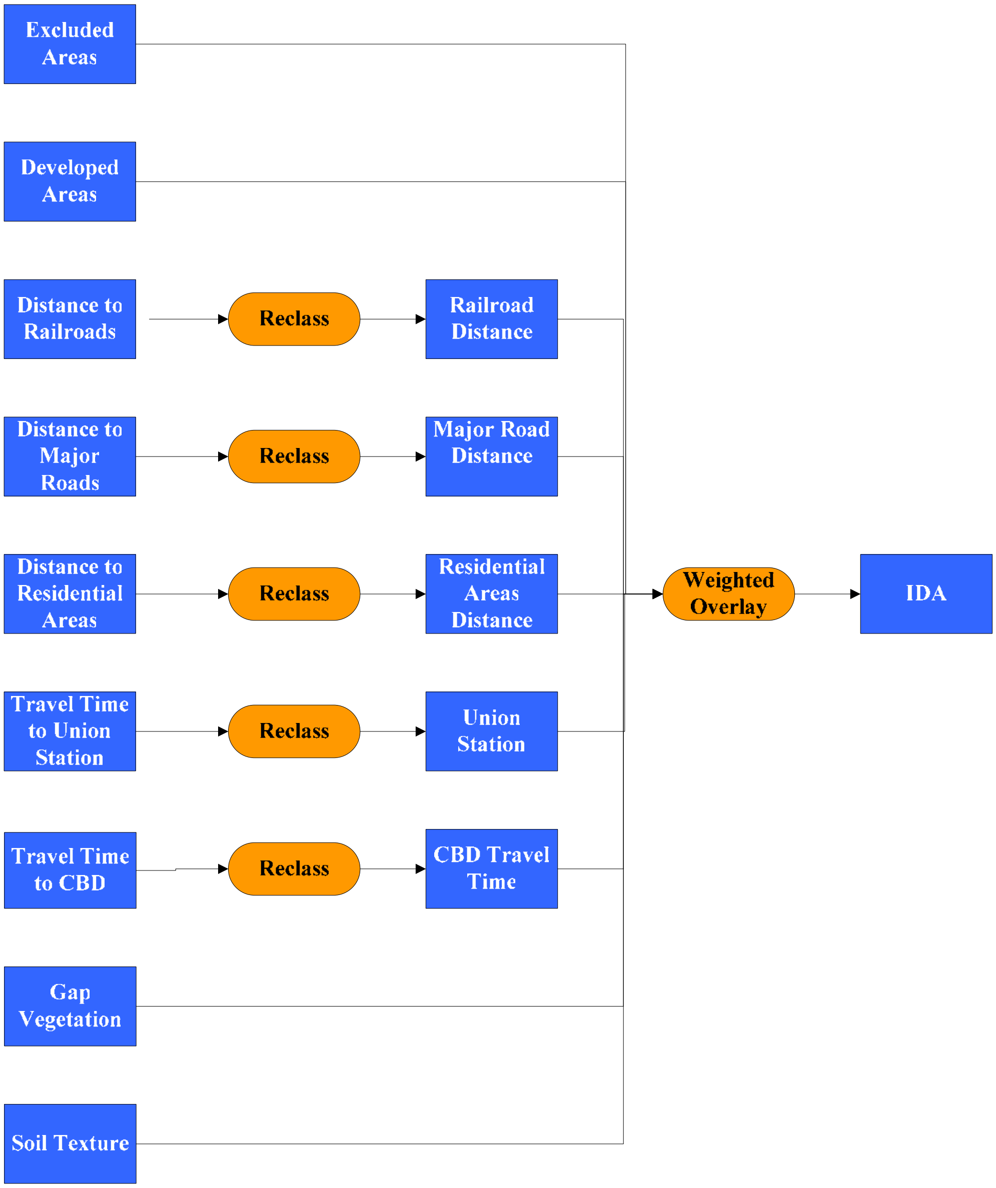


Figure 6. Index of development attractiveness model

Several analyses were derived from other maps. In this case, a map was created that calculated the straight-line distance from the closest roads (Figure 7). GIS can also calculate distance, taking into consideration the relative difficulty of getting from one point to another.

After performing all the overlays, the map in Figure 8 shows the areas identified in red which are most suitable for development.

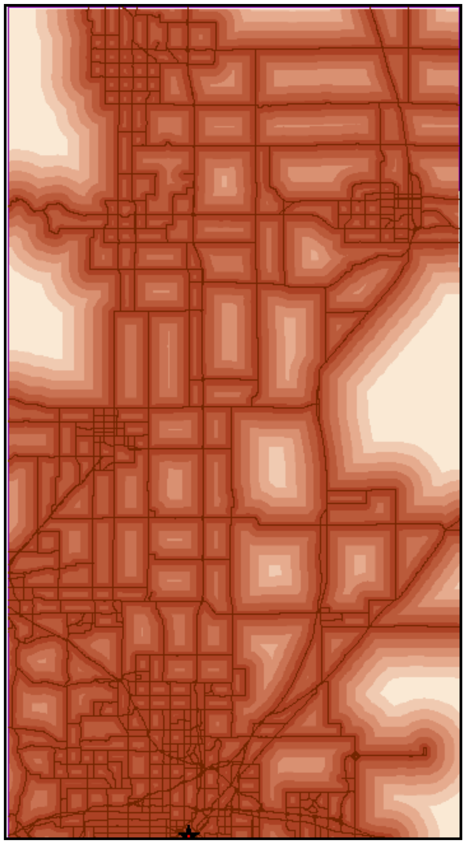


Figure 7. Straight-line calculated distance from roads (Dark areas are closest; light areas are furthest)

When validated against actual historical results, several observations were made. First, the model correctly predicted development patterns 75% of the time, with a tendency to over-predict development. We believe that the accuracy of this model can be improved by refining the assumptions made. However, the initial results are promising.

5.3 Growth Modeling Using a Cellular-Automata Land Use Change Simulator (CALUCS)

An urban growth simulation based on Cellular Automata (CA) considers cities as complex systems with self-organizing mechanisms which are formed by the multitude of interactions that take place on a large scale or at the individual level. The CA model is considered an advancement over the IDA method, but is considerably more complicated

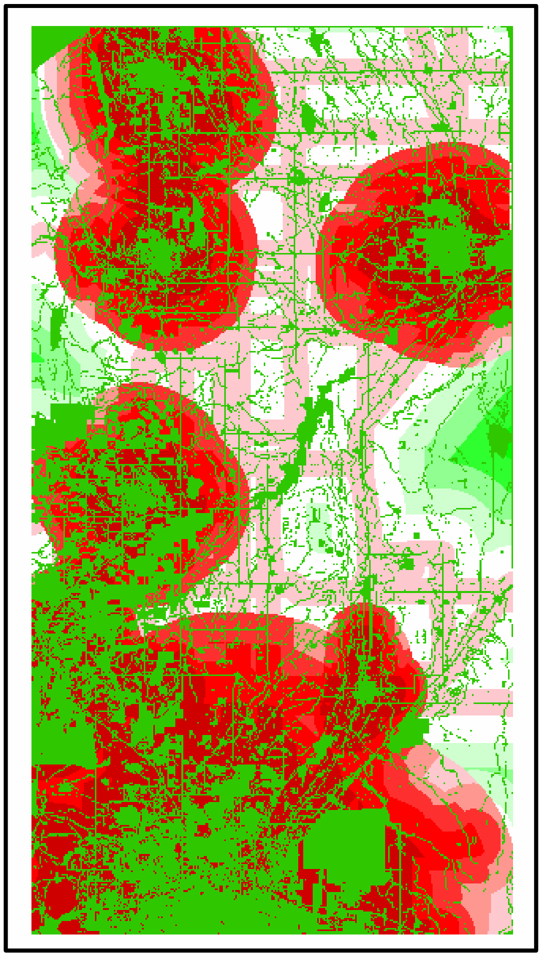


Figure 8. Index of development attractiveness results (The redder areas indicate desirable areas for growth, while green areas indicate areas where growth has already occurred or is unlikely to occur)

and computationally intensive; it requires a supercomputer. It uses many of the same growth factor maps as does the IDA and is therefore limited by inadequate data as well.

An advantage is that the CA method uses the historic land use data to derive the optimal weights for the various factors using historic data. The SLEUTH project is an example of growth modeling that was originally developed by the Geography Department at University of Santa Barbara (Clarke, et.al, 1997). This program has been used and adapted by many researchers in their projects to meet their needs, and the UCD CEA team attempted to use it as the basis for CA modeling. The objective was to develop a more computationally efficient implementation to better accommodate research in the metropolitan Denver area.

Since transition rules are the core of one CA model, the method focuses on calibrating factors (weights) used in the rules. The method considers *local-scale factors* which include interactions between adjacent land uses, and *broad-scale factors* which involve regional interactions due to factors such as a transportation network. When calibrating these factor weights, the system must work backwards. The result of urban growth over time is already known, but the goal is to discover the most significant drivers (factor weights) influencing that growth.

The CA model uses the following various rules to model growth, with the results from each step influencing subsequent ones:

1. **Spontaneous Growth** assumes that development is random across the study area. This means that any non-urbanized cell on the lattice has a certain probability of becoming urbanized at any time.
2. **New Spreading Center Growth** determines whether any of the new spontaneously urbanized cells from the Spontaneous Growth step will become new urban spreading centers, defined by the rule that if a cell is allowed to become a spreading center, at least two additional cells adjacent to the center cell also need to be urbanized.
3. **Edge Growth** stems from existing spreading centers. This growth creates new centers based on what was generated in earlier steps. If a non-urban cell has at least three urbanized neighboring cells, it has a certain probability to also become urbanized as defined by a *Spread_Coefficient*, if it meets certain other conditions.
4. **Transportation-influenced Growth** is the most complicated of the four rules and is determined by the existing transportation infrastructure as well as the most recent urbanization done under rules 1, 2 and 3. With a certain defined probability, newly urbanized cells are selected and the existence of a road is sought in their neighborhoods.

5.4 CALUCS Implementation Status

To provide a better simulation quality over other existing urban development and spatial analysis modeling methods, wavelet transformation, also known as wavelet decomposition, is utilized on the input grid images. Wavelet transform has been explored in digital image processing field gradually since the late 1980's. Compared to the traditional Fourier transformation that cannot localize the analysis of image signal properties with fine resolutions, wavelet transformation tries to exploit redundancies in both time and space scales with varying scaling factors. The transformed data then could be organized into a sub-band structure, which could be more efficiently analyzed. Since a large amount of coverage data are involved in the CDOT CEA modeling (e.g. slope, land use/land cover, vegetation, wildlife and wildlife habitat distribution, and transportation), wavelet transformation is one good choice for disassembling the data into smaller pieces and continuing the divide-and-conquer approach to completing the analyses.

For our implementation the CALUCS modeling software is based on the CA-based SLEUTH model which was originally developed on a CRAY supercomputer. Though the software was written in UNIX C and the majority of the code is relatively easy to convert to other platforms like Microsoft Windows, there may still be some migration difficulties since it uses some language features that are only available on CRAY machines. Now the entire package, with over twenty six thousand lines of source code, has been converted to the Microsoft Windows operating system with new features added in such as a graphical user interface. However, the CALUCS package is not fully operational at this point.

6.0 CUMULATIVE EFFECTS ASSESSMENT ON HABITAT

This section demonstrates how the GIS data on habitat and growth potential can be used to assess cumulative effects. Loss of habitat is a common environmental response to urbanization. Given the base mappings of habitat quality that were created using the HSI approach, and forecasts of land conversion as part of urban growth, a GIS-based overlay procedure was used to identify key areas that may be adversely impacted. A scoring procedure using the product of the HSI times the IDA showed the relative magnitude of the impacts (Figure 9). High values of the HSI x IDA product indicate areas of potential conflict (Figure 10).

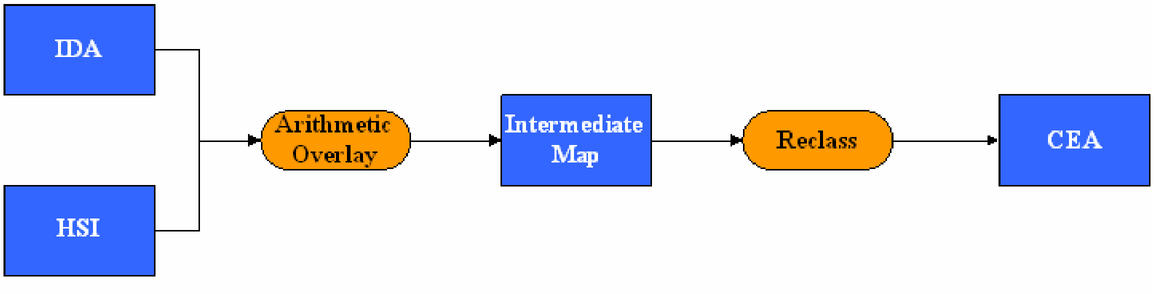


Figure 9. CEA model overlays of IDA map on HSI map

GIS is an excellent way to run multiple scenarios and iterative analyses. Scenario experiments were conducted in which a new roadway project was inserted into the transportation grid, the IDA recomputed, and the differences compared with the base scenario. The map was generated by adding the new feature road, running the model as described earlier, and then subtracting the new map from the old map to identify changes that have occurred due to the new condition. A regional accounting of the changes in development attractiveness is shown in Figure 11.

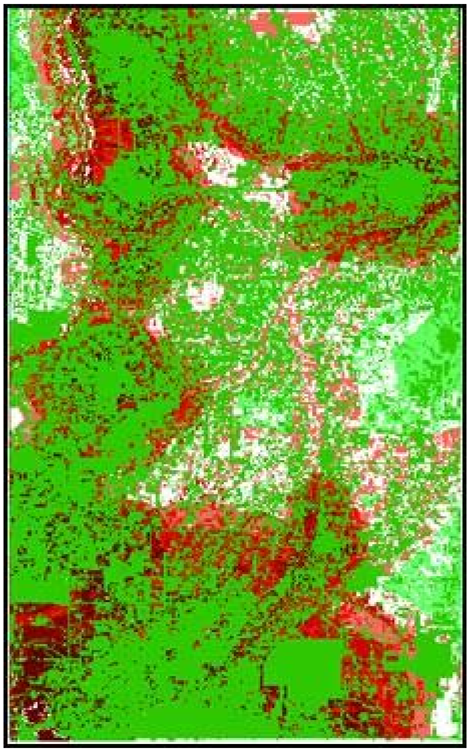


Figure 10. Cumulative effects assessment indicates areas (red) that are susceptible to high potential impacts on habitat

Another application was attempted using the creation of E-470 near the Denver International Airport. The new highway was entered into the transportation network and the IDA factors recomputed. An area near DIA was identified as being potentially attractive for growth given the proximity to the new highway. The effect of the new road was obtained by subtracting the two land use maps. The new predictions can be seen in the dark areas of the map (Figure 12a). Additional growth is attractive between E-470 and Pena Blvd, southwest of DIA, and between Brighton and I-25. The CEA procedure was applied using the new IDA results overlaid onto the HSI map. HSI in the growth area indicates the extent of potential impacts (Figure 120b).

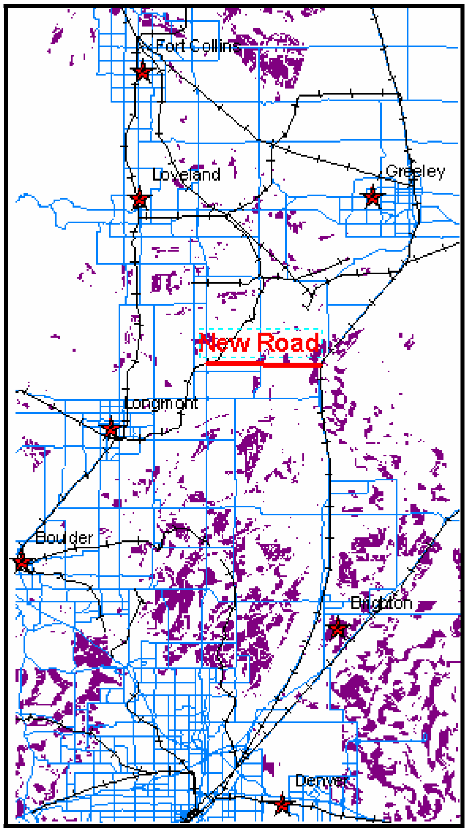
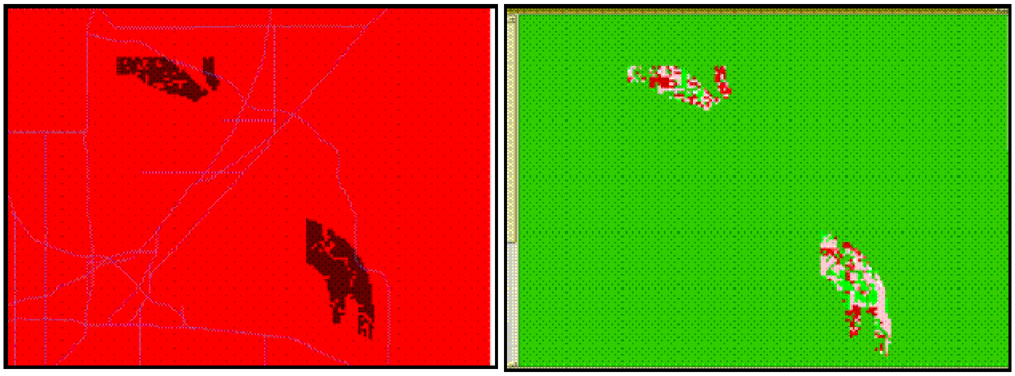


Figure 11. Changes in sensitivity due to the addition of a new road



(a) Predicted growth area

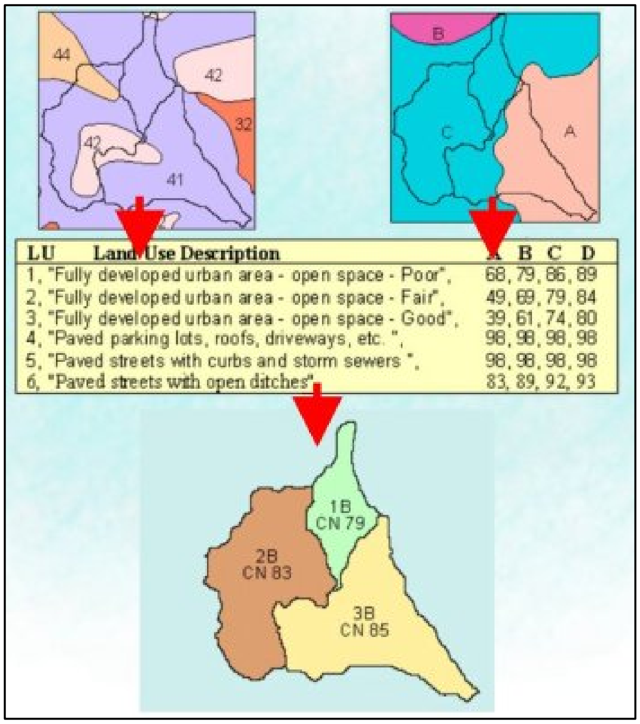
(b) HSI in growth area

Figure 12. New potential growth areas near DIA are identified, and (b) overlay of HSI on the growth areas indicated value of habitat potentially impacted

7.0 HYDROLOGICAL EFFECTS OF LAND USE CHANGE

7.1 Introduction

The objective of this study was to assess the hydrologic impacts of land use change over a discreet period of time by translating the widely accepted TR-55 hydrologic computer model into a GIS model (termed *GIS-55*). GIS-55 is a Watershed Modeling System based on the Soil Conservation Services (SCS) Technical Release #55 (TR-55). Most of the inputs such as slope, length and area can be derived from GIS data products (Figure 13). Combining this data with a Curve Number (a derivative data product of Land Use), a user-defined storm event, and spatial databases for the years 1990 and 2000, enabled the assessment of the hydrologic impacts of land use change over a 10-year period involving 85 watersheds.



LU	Land Use Description	A	B	C	D
1,	"Fully developed urban area - open space - Poor",	68,	79,	86,	89
2,	"Fully developed urban area - open space - Fair",	49,	69,	79,	84
3,	"Fully developed urban area - open space - Good",	39,	61,	74,	80
4,	"Paved parking lots, roofs, driveways, etc. ",	98,	98,	98,	98
5,	"Paved streets with curbs and storm sewers ",	98,	98,	98,	98
6,	"Paved streets with open ditches",	83,	89,	92,	93

Figure 13. Derivation of TR-55 model parameters based on GIS data themes

7.2 Results

The GIS-55 method was used to predict the difference in flood peak resulting from land use change during the decade. Results of the simulations indicate significant increases in flood peaks (Qpeak) due to increased impervious areas associated with residential and commercial land development. Almost every watershed indicated increases in the flood peaks. Peak flows are altered as agricultural or irrigated lands and other areas with high infiltration rates are converted to uses with lower infiltration rates. Common sense and the literature consistently demonstrate that land use change is a one-way street. It always reduces infiltration and increases runoff. The greatest percentage change in peak runoff was for the smaller flood events. The difference is especially pronounced between the 2-year events and the 100-year event values. For example, the maximum percent change in peak flows for the study area between 1990 and 2000 for the 2-year event is 418%. Yet, this difference is just less than 600 cfs. The maximum change in peak flows between 1990 and 2000 for the 100-year event was 77% based on a difference of nearly 5500 cfs.

The model outputs show both a graphical and map representation of the change in a storm peak discharge comparison between the years 1990 and 2000 for 2, 5, 10, 25, 50, and 100 flood events (Figure 14).

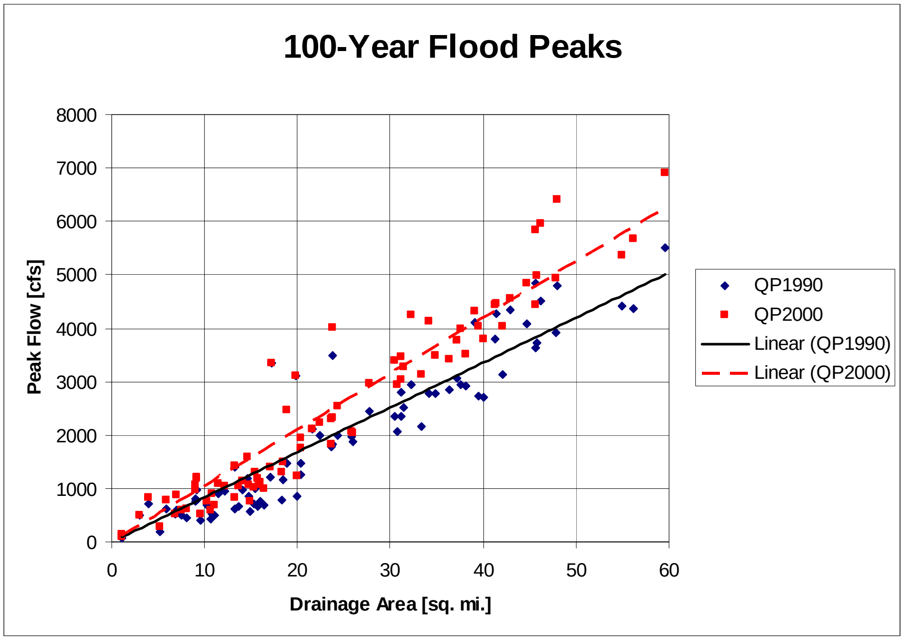


Figure 14. Predicted changes in flood peak for the 100-year event

8.0 CONCLUSIONS

The power in a GIS to manipulate and analyze spatial data is significant. This study has demonstrated a number of techniques for applying this technology to Cumulative Effects Assessments. Overlays, distance functions, reclassifications, and “mapematics” using weighting scales are some of the easiest and most common and were demonstrated in the Habitat Suitability and Land Use Analysis studies. With increasing modeling technology comes additional power to manipulate data and make projections. Examples of these capabilities were demonstrated in the Habitat Suitability, Growth Modeling, Cumulative Effects Assessment and Hydrology Modeling studies.

The GIS-based CEA research and development project has demonstrated achievement of the original objectives of the research project. The research effort was able to collate and organize a regional environmental spatial database relevant to habitat and land use change characterization. Models of habitat suitability had been developed and validation showed reasonable correspondence with mapped prairie dog colonies. Development attractiveness indexing based on growth relevant factors was used to identify lands which would be susceptible to conversion to urban uses. Scenarios of new projects and differencing comparison to base conditions can be used to assess possible alternate routes or to help plan mitigation measures such as habitat enhancement in non-threatened areas.

In spite of the great potential demonstrated by the use of GIS-based CEA databases and models, there remain significant issues. The habitat characterizations are limited by the quality of the vegetation mapping. UCD is working to develop image processing and multi-scale imagery merging procedures to take advantage of high resolution aerial photography in the habitat characterization process. This is particularly important for the riparian zones.

Further, the accuracy of the IDA approach needs to be further validated. The IDA approach is straight forward in concept and application, but may be limited by its deterministic nature. UCD is working on a stochastic cellular automata (CA) model which would provide more rigorous validation of urban growth processes.

Additional work with these and similar data should be analyzed within a CEA framework to include additional studies such as potential time and space crowding, time lags, habitat fragmentation, compounding from multiple sources or pathways, indirect or secondary effects, and fundamental changes in system behavior or structure because of triggers or crossing sustainability thresholds. Many of these are appropriately handled within a GIS geospatial database, and many can be accomplished with some of the simpler techniques which were explored in this research study.

CEA has historically not been accomplished to its fullest potential. It is the wish of the researchers that this study will move the depth of analysis and potential for this valuable tool forward.

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