GIS-based Multi-Criteria Decision Analysis
(in Natural Resource Management)

Ronald C. Estoque
(Student ID Number: 201030243)
D1 – Division of Spatial Information Science

2011

Learning objective

- The aim of this lecture presentation is to present the basic principles, methods, & some applications of GIS-based Multi-criteria Decision Analysis (MCDA).

Outline

- Introduction
- Basic principles of GIS-based MCDA
- Methods & applications of multi-criteria evaluation
- Remarks

Introduction

- **Land** is a scarce natural resource
  - The demand is continuously growing
    - to satisfy human beings' basic needs, & insatiable wants & desires
  - People must select the best use of this resource
    - uphold sustainability to be able to sustain the benefits this resource provides for the next generations to come
  - However, people have different behaviors, beliefs, knowledge, priorities, goals, interests & concerns
    - decision-making on how a particular resource should be utilized is not an easy task

Basic principles of GIS-based MCDA

MCDA – Multi-Criteria Decision Analysis

- **Problem**
  - *spatial decision problems* typically involve a large set of feasible alternatives & multiple evaluation criteria
    - most of the time, these are conflicting
  - alternatives & criteria are often evaluated by a number of individuals (decision-makers, managers, stakeholders, interest groups).
    - most of the time, they also have conflicting ideas, preferences, objectives, etc.
  - many spatial decision problems give rise to the GIS-based MCDA
    - to aid in the decision making process
- **GIS**
  - techniques & procedures have an important role to play in analyzing decision problems
    - recognized as a decision support system involving the integration of spatially referenced data in a problem solving environment
- **MCDA**
  - provides a rich collection of techniques & procedures for structuring decision problems, & designing, evaluating & prioritizing alternative decisions
- **GIS-MCDA**
  - can be thought of as a process that transforms & combines geographical data & value judgments (the decision-maker's preferences) to obtain information for decision making

See Malczewski (2006)

Basic principles of GIS-based MCDA

Definitions

- **Decision** – is a choice between alternatives
  - *i.e.* best land use among different land use alternatives
- **Criteria**
  - are set of guidelines or requirements used as basis for a decision
  - Two types: *factors* & *constraints*
    - A **factor** is a criterion that enhances or detracts from the suitability of a specific alternative for the activity under consideration
      - *i.e.* distance to road (near = most suitable; far = least suitable)
    - A **constraint** serves to limit the alternatives under consideration; element or feature that represents limitations or restrictions; area that is not preferred in any way or considered unsuitable.
      - *i.e.* protected area, water body, etc. (usually represented by a Boolean mask)

See Eastman et al. (1995)

Basic principles of GIS-based MCDA

Definitions

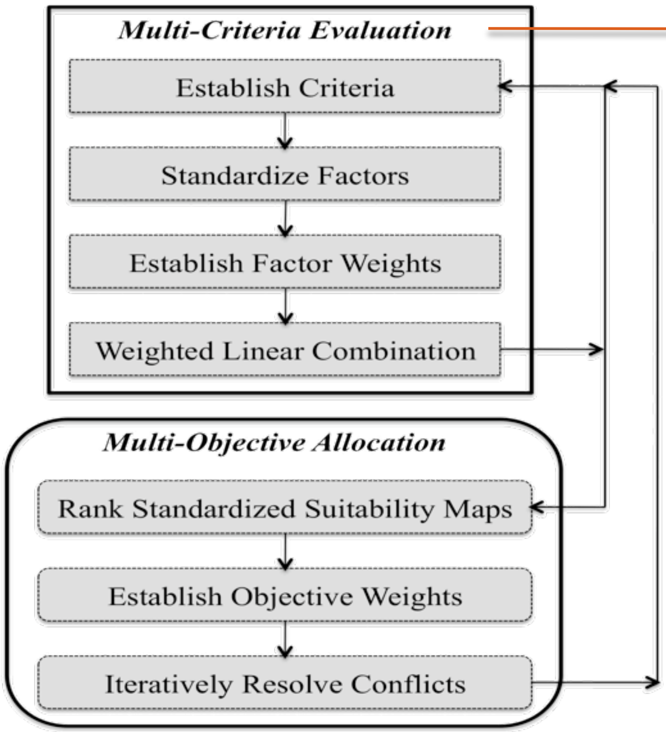
- **Decision rule**
  - procedure by which criteria are combined to arrive at a particular evaluation.
  - 1) Choice function – provides a mathematical means for comparing alternatives; numerical, exact decision rules
  - 2) Choice heuristic – specifies a procedure to be followed rather than a function
- **Objective**
  - the measure by which the decision rule operates (*i.e.* identify suitable areas for a housing project)
  - in a single-objective multi-criteria evaluation, it is also considered as a 'goal'
- **Suitability**
  - is the characteristic of possessing the preferred attributes or requirements for a specific purpose
- **Suitability analysis**
  - is a GIS-based process used to determine the appropriateness of a given area (land resource) for a specific use, *i.e.* agriculture, forestry, business, urban development, livelihood projects, etc.

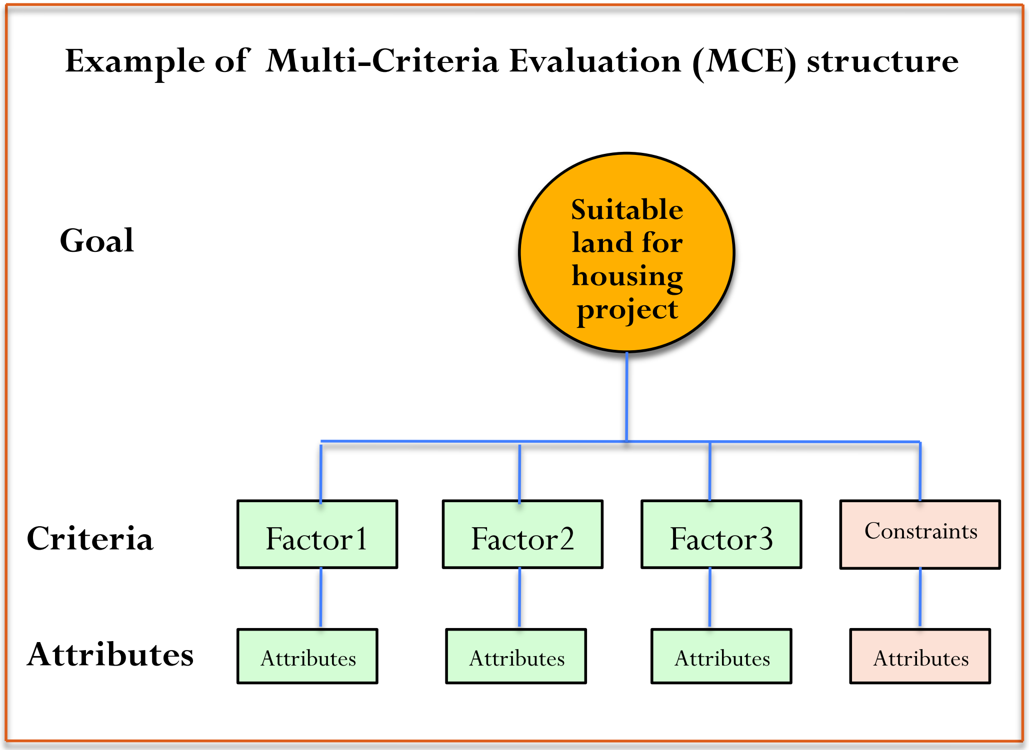
See Eastman et al. (1995)

Basic principles of GIS-based MCDA

- Multi-Criteria Decision Making/Analysis (MCDM/MCDA)
  - **Multi-Criteria Evaluation**
    - sometimes it is also referred to as multi-attribute evaluation or Multi-Attribute Decision Analysis (MADA)
    - **Example**: *site suitability analysis for housing development (specific single objective)*
  - **Multi-Objective Evaluation**
    - sometimes it is also called as Multi-Objective Decision Analysis (MODA)
    - Example: *analysis for best land use (forest, agriculture, residential, etc.) - multiple objectives*
      - 1) suitability analysis per land use; 2) Multi-Objective Land Allocation (MOLA)

GIS-based MCDA (*Adopted from* Eastman et al., 1995)





Methods of Multi-Criteria Evaluation (MCE)

Steps:

1. Set the goal/define the problem
2. Determine the criteria (factors/constraints)
3. Standardize the factors/criterion scores
4. Determine the weight of each factor
5. Aggregate the criteria
6. Validate/verify the result

Methods of Multi-Criteria Evaluation (MCE)

- **Steps**
  1. Set the goal/define the problem
     - As a general rule, a goal must be:

S – specific
M – measurable
A – attainable
R – relevant
T – time-bound

Source: Haugey, D. "SMART Goals". Project Smart. www.projectsmart.co.uk/smart-goals.html

Methods of Multi-Criteria Evaluation (MCE)

- **Steps**

  2. Determine the criteria (factors/constraints)

     - how much details are needed in the analysis affects the set of criteria to be used
       - *i.e.* main roads only vs. including minor roads; no. of houses vs. no. of residents; etc.
     - Criteria should be measurable
     - If not determinable, use proxies
       - *i.e.* slope stability can be represented by slope gradient

Methods of Multi-Criteria Evaluation (MCE)

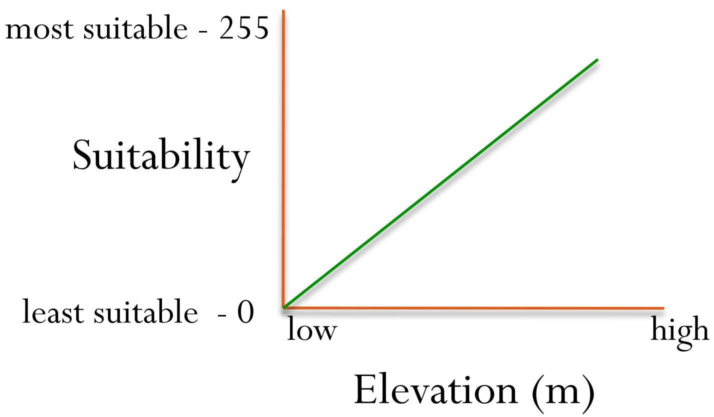
- **Steps**

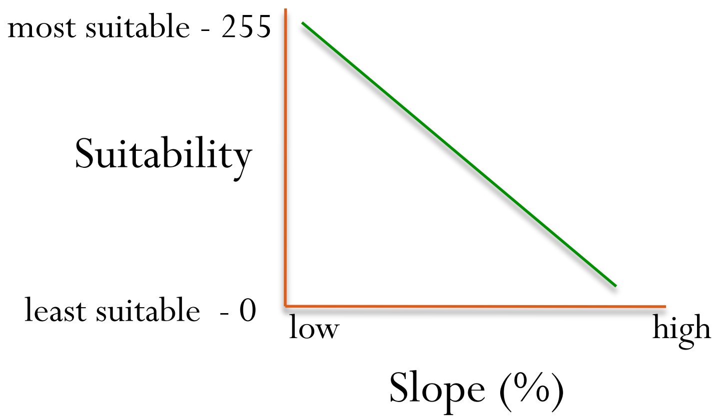
  3. Standardize the factors/criterion scores

     - Set the suitability values of the factors to a common scale to make comparisons possible
       - it is hard to compare different things (*i.e.* mango vs. banana)

       For example

       - Elevation (m)
       - Slope (%)
         - Convert them to a common range, i.e. 0 – 255
         - 0 = least suitable; 255 = most suitable



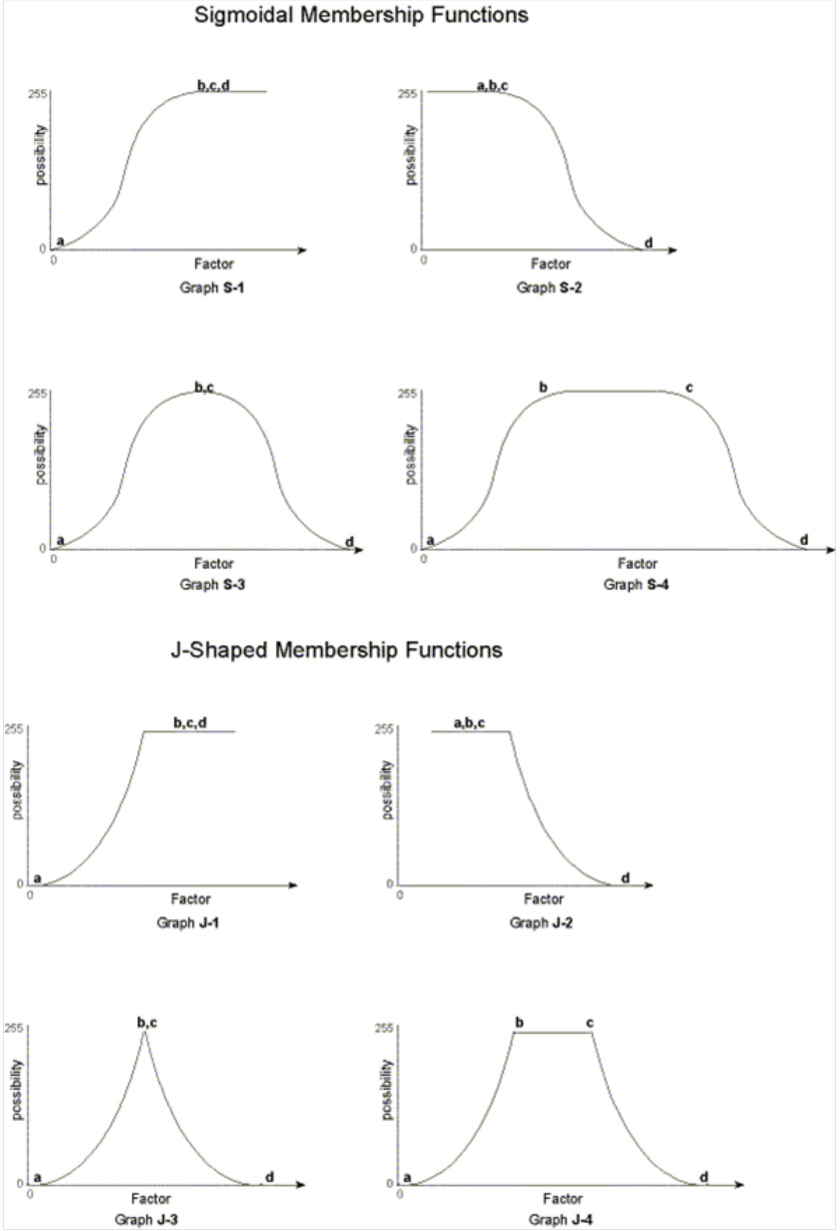


Methods of MCE

- **Steps**

  3. Standardize the factors/ criterion scores *cont'd…*

     - **Fuzzy Membership Functions** are used to standardize the criterion scores.
     - Decision-makers have to decide based on their knowledge & fair judgment which function should be used for each criterion.



Linear Membership Function

Source *(Figures)*: Eastman (1999; 2006)

Methods of Multi-Criteria Evaluation (MCE)

- **Steps**

  4. Determine the weight of each factor

     - There are several methods
       - **Ranking**
         - *i.e.* 3 factors: rank the factors with 1, 2, & 3, where 1 is the least important while 3 is the most important
       - **Rating**
         - *i.e.* 3 factors: rate the factors using percentile – Factor 1 with the lowest percentage as the least important & Factor 3 with the highest percentage as the most important

       - *Rankings & ratings are usually converted to numerical weights on a scale 0 to 1 with overall summation of 1 (normalization).*
       - *i.e.* Factor 1 = 0.17; Factor 2 = 0.33; & Factor 3 = 0.50;

Methods of Multi-Criteria Evaluation (MCE)

- **Steps**

  4. Determine the weight of each factor

     - There are several methods *(cont'd)*
       - **Pairwise comparison**

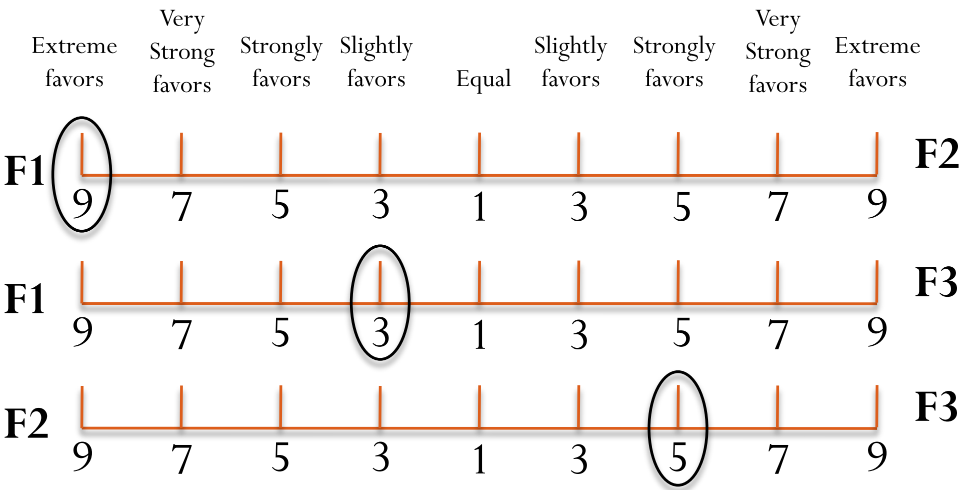
         Analytical Hierarchy Process **(AHP)** (Saaty, 1980)

         - A matrix is constructed, where each criterion is compared with the other criteria, relative to its importance, on a scale from 1 to 9.
           - where 1 = *equal preference* between two factors; 9 = a particular factor is *extremely favored* over the other
           - a weight estimate is calculated & used to derive a consistency ratio (CR) of the pairwise comparisons
             - If CR > 0.10, then some pairwise values need to be reconsidered & the process is repeated until the desired value of CR < 0.10 is reached.
         - Like in ranking & rating, AHP weights are also expressed in numerical weights that sum up to 1.

4. Determine the weight of each factor (using AHP)

Example: Using 3 factors

Step 1 – Compare the factors



Note: 2, 4, 6 & 8 are intermediate values. F1, F2, & F3 are factors.

Step 2 – Complete the matrix

	F1	F2	F3
F1	1	9	3
F2	1/9	1	1/5
F3	1/3	5	1
Σ	1.4444	15.0000	4.2000

Note: Values in blue are reciprocals.

Basic rules:

1. If the judgment value is on the left side of 1, we put the actual judgment value.
2. If the judgment value is on the right side of 1, we put the reciprocal value .

Step 3 – Normalization & weight determination

	F1	F2	F3	Priority vector* or Weight
F1	0.6923	0.6000	0.7143	0.6689
F2	0.0769	0.0667	0.0476	0.0637
F3	0.2308	0.3333	0.2381	0.2674

*Priority vector is also called normalized principal Eigen vector.

- To normalize the values, divide the cell value by its column total.
- To calculate the priority vector or weight, determine the mean value of the rows.

Step 4 – Calculate the Consistency Ratio (CR)

CR = Consistency index (CI)/Random Consistency Index (RI)

- CI = (λ_{max} – n)/n – 1
  - λ_{max} is the Principal Eigen Value; ***n*** is the number of factors
- λ_{max} = Σ of the products between each element of the priority vector and column totals.
  - λ_{max} = (1.44*0.67) + (15*0.06) + (4.20*0.27) = 3.0445
  - CI = (3.0445 – 3)/3-1   CI = 0.0445/2   CI = 0.0222
  - CR = 0.0222/0.58   **CR = 0.04 < 0.10 (Acceptable)**

Random Consistency Index (RI) (Saaty, 1980).

n -	1	2	3	4	5	6	7	8	9	10
RI -	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Methods of Multi-Criteria Evaluation (MCE)

- **Steps**

  5. Aggregate the criteria

     - **Weighted Linear Combination**
       - is the most commonly used decision rule

Formula: $S = \sum w_i x_i \times \prod c_j$

Where:

S – is the composite suitability score

x_i – factor scores (cells)

w_i – weights assigned to each factor

c_j – constraints (or Boolean factors)

$\sum$ -- sum of weighted factors

$\prod$ -- product of constraints (1-suitable, 0-unsuitable)

- *Example:*

  Applying it in GIS raster calculator

  S =((F1 * 0.67) + (F2 * 0.06) + (F3 * 0.27)) * cons_boolean

Note: F1, F2, F3 & cons_boolean are thematic layers representing the factors & constraints.

Methods of Multi-Criteria Evaluation (MCE)

- **Steps**
  6. Validate/verify the result
     - to assess the reliability of the output
       - Ground truth verification
         - *i.e.* conduct a field survey to verify sample areas
       - Sensitivity analysis
         - How do the following affect the result?
           - altering the set of criteria (plus or minus)
           - altering the respective weights of the factors
         - Is the result reasonable?
         - Does the result reflect reality?
         - Etc.

Examples: Applications of GIS-based MCE

1. Suitability analysis for beekeeping sites in La union, Philippines, using GIS & MCE techniques

- Goal
  - to produce a map showing the suitable areas for beekeeping
- Criteria

Factors

Categorical data

- Land use/cover – scores/suitability values (0-255) assigned to the different land uses/covers were based on the availability of source of nectar and pollen

Continuous data

- Distance to river – standardized to 0-255 scale: suitability values decreases with the distance to river
- Distance to road – standardized to 0-255 scale: suitability values decreases with the distance to road (starting from a buffer of 25 m).
- Elevation – standardized to 0-255 scale: suitability values decreases with elevation

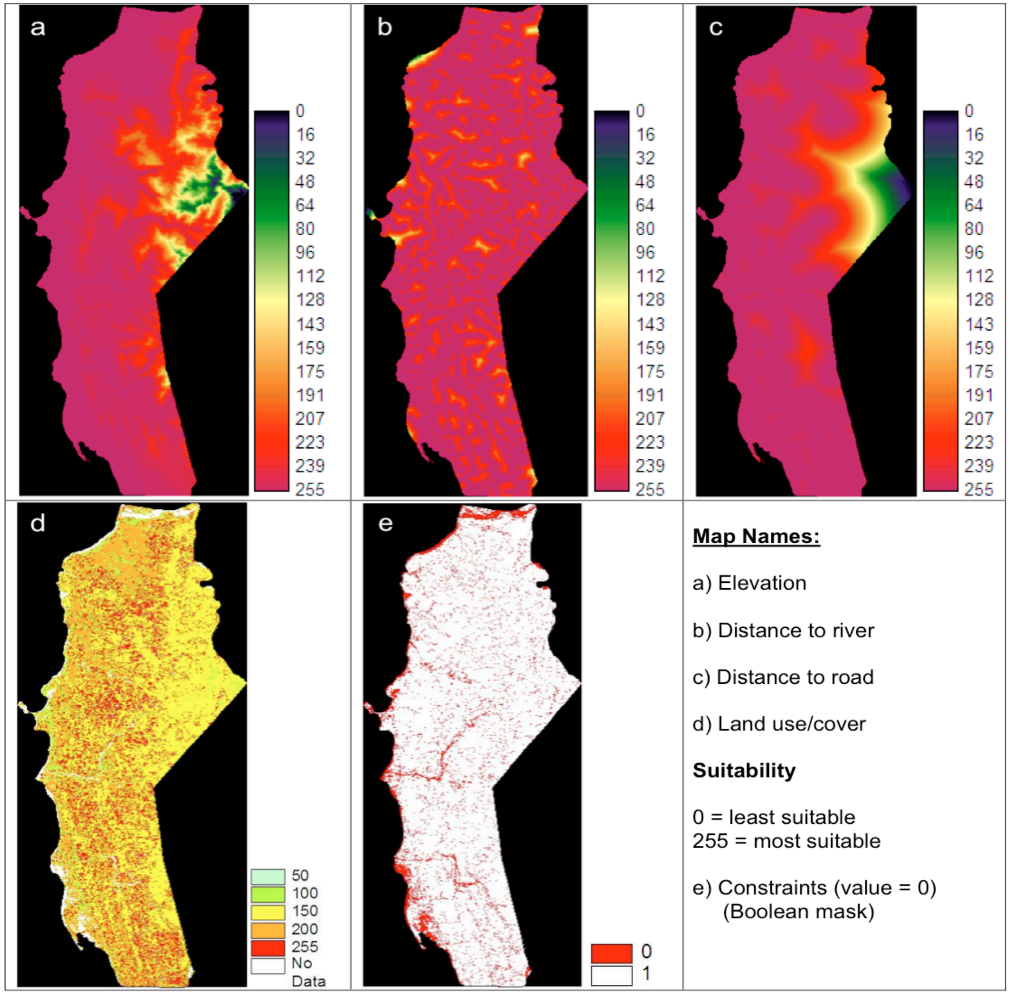
Constraints

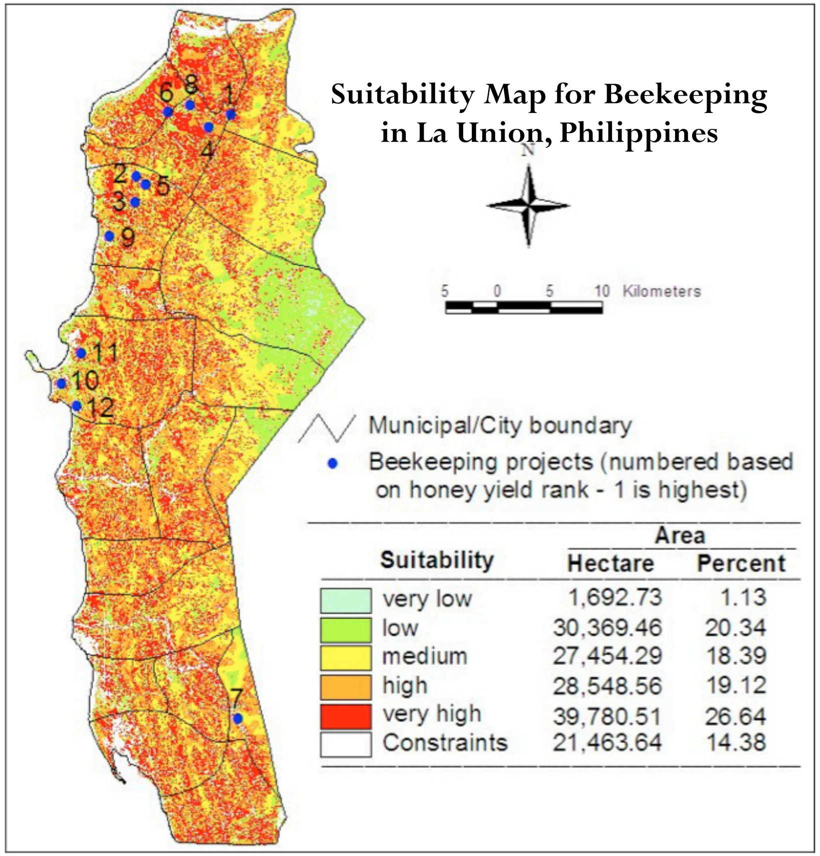
- built-up areas, sand, water body, riverwash, & areas within 25 m from the roads

For more details, see: Estoque, R C & Murayama, Y (2010). Suitability analysis for beekeeping sites in La union, Philippines, using GIS & MCE techniques. *Research Journal of Applied Sciences*, 5, 242 – 253.

Also in: (as a book chapter) Murayama, Y & Thapa, R B (Eds), *Spatial Analysis and Modeling in Geographical Transformation Process: GIS-based Applications*. Dordrecht: Springer Science +Business Media B.V., isbn:978-94-007-0670-5

1. Suitability analysis for beekeeping sites using GIS & MCE techniques *cont'd…*





Using Raster Calculator: (Weighted Overlay tool can also be used)

S =((elevation * 0.0553) + (dist_river * 0.2622) + (dist_road * 0.1175) + (luc * 0.5650)) * cons_boolean

For more details, see: Estoque, R C & Murayama, Y (2010). Suitability analysis for beekeeping sites in La union, Philippines, using GIS & MCE techniques. *Research Journal of Applied Sciences*, 5, 242 – 253.

Also in: *(as a book chapter)* Murayama, Y & Thapa, R B (Eds), *Spatial Analysis and Modeling in Geographical Transformation Process: GIS-based Applications*. Dordrecht: Springer Science +Business Media B.V., isbn:978-94-007-0670-5

Examples: Applications of GIS-based MCE

2. Suitability analysis for best site for a new school

- Goal
  – to produce a map showing the best site for a new school
- Criteria

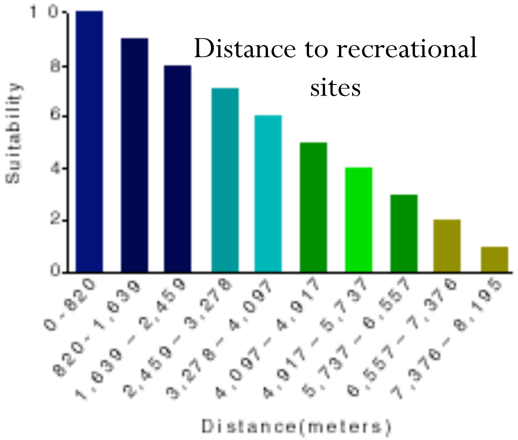
  Factors
  - Distance to recreational sites – areas near to recreational facilities are preferred
  - Distance to existing schools – areas away from existing schools are preferred
  - Slope – areas on flat terrain are preferred
  - Land use – agricultural land is most preferred followed by barren land, bush/transitional areas, forest, & built-up areas.

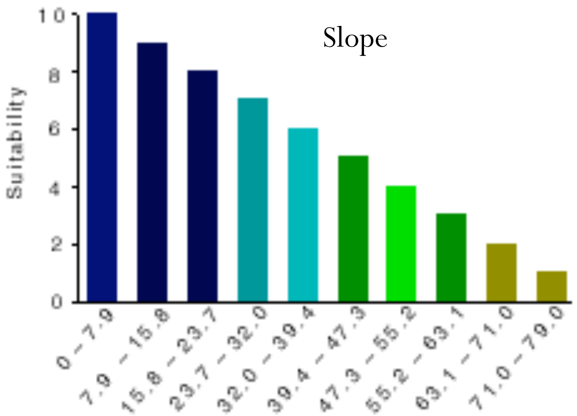
  Constraints
  - Water & wetlands

For more details, see: ESRI (2007). Using the conceptual model to create a suitability map. ArcGIS Tutorial. webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=tutorials

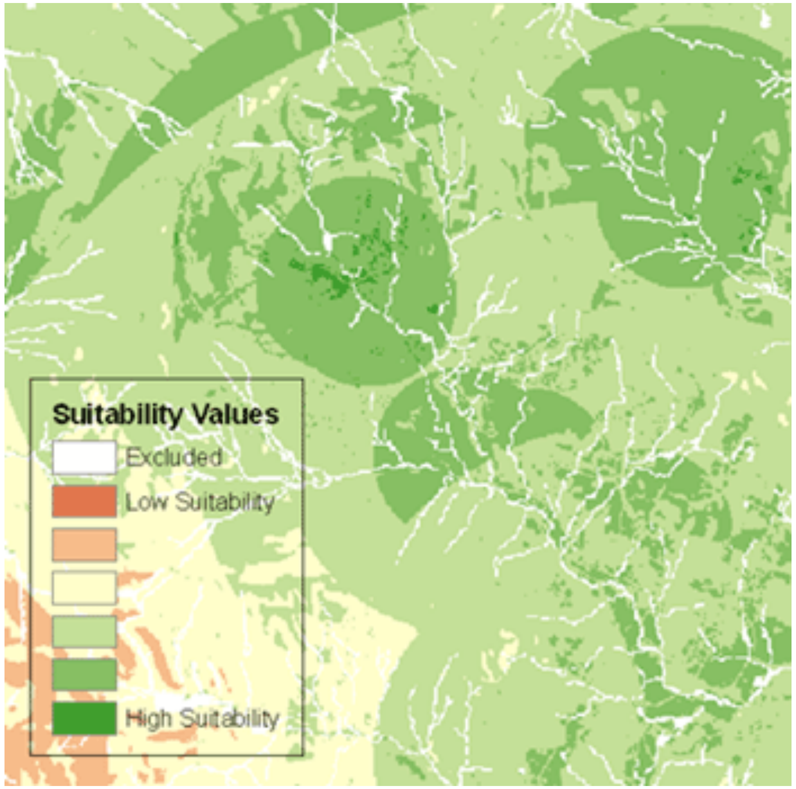
2. Suitability analysis for best site for a new school

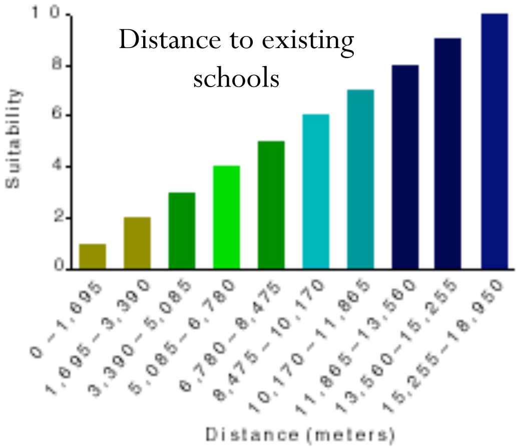
cont'd…

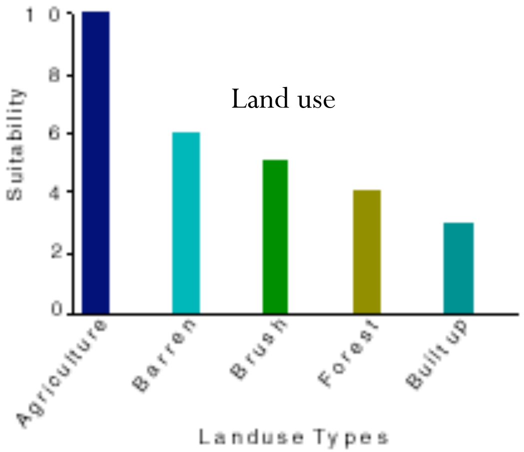




Suitability map for best site for a new school







Standardization method:

Continuous data – re-classed (10 classes) & assigned a suitability value per class using a scale of 1 – 10 (10 = most suitable; 1 = least suitable)

Categorical data (land use) - assigned a suitability value per class using a scale of 1 – 10 (10 = most suitable; 1 = least suitable)

Using Raster Calculator: (Weighted Overlay can also be used)

S =((dist_rec * 0.50) + (dist_school * 0.25) + (slope * 0.125) + (luc * 0.125)) * cons_boolean

Note: In this presentation, "cons_bool" was added to represent the constraints.

For more details, see: ESRI (2007). Using the conceptual model to create a suitability map. ArcGIS Tutorial. webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=tutorials

Remarks

- GIS-based MCDA particularly MCE is good for complex scenarios.
  - *i.e.* site/land suitability analysis – involves multiple criteria & a lot more considerations
- However, MCDA/MCE's nature of being "participatory" sometimes raises subjectivity.
  - *i.e.* in choosing the criteria & defining the weights of each factor
- GIS packages
  - IDRISI Andes/Taiga have the following decision support modules: Fuzzy (used to standardize factors), Weight (used to calculate the AHP weights), MCE (for the actual evaluation), & a lot more.
  - The whole MCE process can also be done in ArcGIS (model builder) although it may not have the standardization functionalities like what IDRISI has.

References & Suggested Readings

- Eastman, R J (2006). Idrisi Andes: Guide to GIS and image processing. Clark Labs, Clark University, Worcester, USA.
- Eastman, R J (1999). IDRISI 32 – Guide to GIS and Image Processing, Volume 2. Clark Labs, Clark University, Worcester, USA.
- Eastman, R J, Jin, W, Kyem, P A, & Toledano, J (1995). Raster procedure for multi-criteria/multi-objective decisions. *Photogrammetric Engineering and Remote Sensing*, 61, 539 – 547.
- ESRI (2007). Using the conceptual model to create a suitability map. ArcGIS Tutorial. Accessed January 11, 2011. webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=tutorials
- Estoque, R C and Murayama, Y (2011). Beekeeping sites suitability analysis integrating GIS and MCE techniques. In Murayama, Y and Thapa, R B (Eds), *Spatial Analysis and Modeling in Geographical Transformation Process: GIS-based Applications*. Dordrecht: Springer Science +Business Media B.V., isbn:978-94-007-0670-5
- Estoque, R C & Murayama, Y (2010). Suitability analysis for beekeeping sites in La union, Philippines, using GIS & MCE techniques. *Research Journal of Applied Sciences*, 5, 242 – 253.
- Haugey, D. "SMART Goals". Project Smart. Accessed January 11, 2011.

  www.projectsmart.co.uk/smart-goals.html
- Malczewski, J (2006). GIS-based multicriteria decision analysis: a survey of the literature. *International Journal of Geographical Information Science*, 20, 703 – 726.
- Malczewski, J (2004). GIS-based land-use suitability analysis: a critical overview. *Progress in Planning*, 62, 3 – 65.
- Saaty, T L (1980). *The Analytic Hierarchy Process*. New York: McGraw Hill.
- Teknomo, K (2006). Analytic Hierarchy Process (AHP) Tutorial . Accessed January 11, 2011.

  http://people.revoledu.com/kardi/tutorial/ahp/