Exercise 2-6
Map Algebra

In Exercises 2-2 and 2-4, we used the OVERLAY module to perform Boolean (or logical) operations. However, this module can also be used as a general arithmetic operator between images. This then leads to another important set of operations in GIS called Map Algebra.

Map Algebra refers to the use of images as variables in normal arithmetic operations. With a GIS, we can undertake full algebraic operations on sets of images. In the case of IDRISI, mathematical operations are available through three modules: OVERLAY, TRANSFORM, and SCALAR (and by extension through the Image Calculator, which includes the functionality of these three modules). While OVERLAY performs mathematical operations between two images, SCALAR and TRANSFORM both act on a single image. SCALAR is used to mathematically change every pixel in an image by a constant. For example, with SCALAR we can change a relief map from meters to feet by multiplying every pixel in the image by 3.28084. TRANSFORM is used to apply a uniform mathematical transformation to every pixel in an image. For example, TRANSFORM may be used to calculate the reciprocal (one divided by the pixel value) of an image, or to apply logarithmic or trigonometric transformations.

These three modules give us mathematical modeling capability. In this exercise, we will work primarily with SCALAR, OVERLAY, and Image Calculator. We will also use a module called REGRESS, which evaluates relationships between images or tabular data to produce regression equations. The mathematical operators will then be used to evaluate the derived equations. Those who are unfamiliar with regression modeling are encouraged to further investigate this important tool by consulting a statistics text. We will also use the CROSSTAB module, which produces a new image based on all the unique combinations of values from two images.

In this exercise, we will create an agro-climatic zone map for the Nakuru District in Kenya. The Nakuru District lies in the Great Rift Valley of East Africa and contains several lakes that are home to immense flocks of pink flamingos.

a) Display the image NRELIEF with the IDRISI Default Quantitative palette.[48]

This is a digital elevation model for the area. The Rift Valley appears in the dark black and blue colors, and is flanked by higher elevations shown in shades of green.

An agro-climatic zone map is a basic means of assessing the climatic suitability of geographical areas for various agricultural alternatives. Our final image will be one in which every pixel is assigned to its proper agro-climatic zone according to the stated criteria.

The approach illustrated here is a very simple one adapted from the 1:1,000,000 Agro-Climatic Zone Map of Kenya (1980, Kenya Soil Survey, Ministry of Agriculture). It recognizes that the major aspects of climate that affect plant growth are moisture availability and temperature. Moisture availability is an index of the balance between precipitation and evaporation, and is calculated using the following equation:

moisture availability = mean annual rainfall / potential evaporation[49]

While important agricultural factors such as length and intensity of the rainy and dry seasons and annual variation are not

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48. For this exercise, make sure your User Preferences are set to the default values by opening File/User Preferences and pressing the Revert to Defaults button. Click OK to save the settings.

49. The term *potential* evaporation indicates the amount of evaporation that *would* occur if moisture were unlimited. Actual evaporation may be less than this, since there may be dry periods in which there is simply no moisture available to evaporate.

accounted for in this model, this simpler approach does provide a basic tool for national planning purposes.

The agro-climatic zones are defined as specific combinations of moisture availability zones and temperature zones. The value ranges for these zones are shown in Table 1.

Moisture Availability Zone	Moisture Availability Range
7	<0.15
6	0.15 - 0.25
5	0.25 - 0.40
4	0.40 - 0.50
3	0.50 - 0.65
2	0.65 - 0.80
1	>0.80

Temperature Zone	Temperature Range (°C)
9	<10
8	10 - 12
7	12 - 14
6	14 - 16
5	16 - 18
4	18 - 20
3	20 - 22
2	22 - 24
1	24 - 30

Table 1

For Nakuru District, the area shown in the image NRELIEF, three data sets are available to help us produce the agro-climatic zone map:

i) a mean annual rainfall image named NRAIN;

ii) a digital elevation model named NRELIEF;

iii) tabular temperature and altitude data for nine weather stations.

In addition to these data, we have a published equation relating potential evaporation to elevation in Kenya.

Let's see how these pieces fit into a conceptual cartographic model illustrating how we will produce the agro-climatic zones map. We know the final product we want is a map of agro-climatic zones for this district, and we know that these zones are based on the temperature and moisture availability zones defined in Table 1. We will therefore need to have images representing the temperature zones (which we'll call TEMPERZONES) and moisture availability zones (MOIST-ZONES). Then we will need to combine them such that each unique combination of TEMPERZONES and MOIST-ZONES has a unique value in the result, AGROZONES. The module CROSSTAB is used to produce an output image in which each unique combination of input values has a unique output value.

To produce the temperature and moisture availability zone images, we will need to have continuous images of temperature and moisture availability. We will call these TEMPERATURE and MOISTAVAIL. These images will be reclassified according to the ranges given in Table 1 to produce the zone images. The beginning of the cartographic model is constructed in Figure 1.

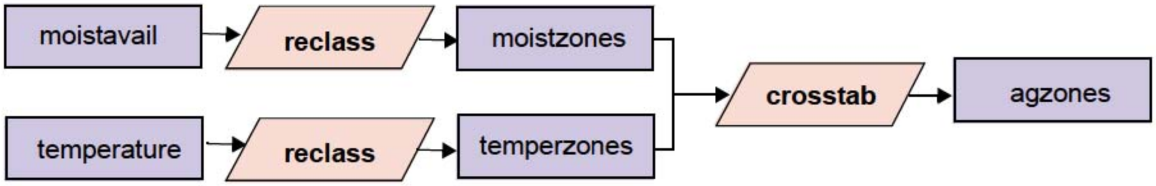

Figure 1

Unfortunately, neither the temperature image nor the moisture availability image are in the list of available data—we will need to derive them from other data.

The only temperature information we have for this area is from the nine weather stations. We also have information about the elevation of each weather station. In much of East Africa, including Kenya, temperature and elevation are closely correlated. We can evaluate the relationship between these two variables for our nine data points, and if it is strong, we can then use that relationship to derive the temperature image (TEMPERATURE) from the available elevation image.[50]

The elements needed to produce TEMPERATURE have been added to this portion of the cartographic model in Figure 2. Since we do not yet know the exact nature of the relationship that will be derived between elevation and temperature, we cannot fill in the steps for that portion of the model. For now, we will indicate that there may be more than one step involved by leaving the module as unknown (????).

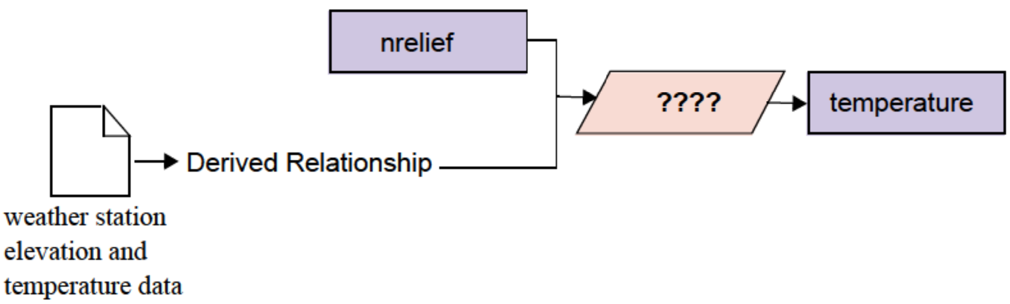

Figure 2

Now let's think about the moisture availability side of the problem. In the introduction to the problem, moisture availability was defined as the ratio of rainfall and potential evaporation. We will need an image of each of these, then, to produce MOISTAVAIL. As stated at the beginning of this exercise, OVERLAY may be used to perform mathematical operations, such as the ratio needed in this instance, between two images.

We already have a rainfall image (NRAIN) in the available data set, but we don't have an image of potential evaporation (EVAPO). We do have, however, a published relationship between elevation and potential evaporation. Since we already have the elevation model, NRELIEF, we can derive a potential evaporation image using the published relationship. As before, we won't know the exact steps required to produce EVAPO until we examine the equation. For now, we will indicate that there may be more than one operation required by showing an unknown module symbol in that portion of the

50. A later tutorial exercise on Geostatistics presents another method for developing a full raster surface from point data.

cartographic model in Figure 3.

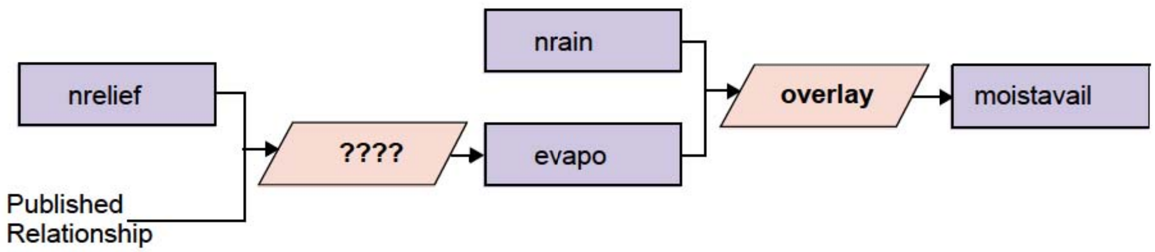

Figure 3

Now that we have our analysis organized in a conceptual cartographic model, we are ready to begin performing the operations with the GIS. Our first step will be to derive the relationship between elevation and temperature using the weather station data, which are presented in Table 2.

Station Number	Elevation (ft)	Mean Annual Temp. (°C)
1	7086.00	15.70
2	7342.00	14.90
3	8202.00	13.70
4	9199.00	12.40
5	6024.00	18.20
6	6001.00	16.80
7	6352.00	16.30
8	7001.00	16.30
9	6168.00	17.20

Table 2

We can see the nature of the relationship from an initial look at the numbers—the higher the elevation of the station, the lower the mean annual temperature. However, we need an equation that describes this relationship more precisely. A statistical procedure called regression analysis will provide this. In IDRISI, regression analysis is performed by the module REGRESS.

REGRESS analyzes the relationship either between two images or two attribute values files. In our case, we have tabular data and from it we can create two attribute values files using Edit. The first values file will list the stations and their elevations, while the second will list the stations and their mean annual temperatures.

b) Use Edit from the Data Entry menu, first to create the values file ELEVATION, then again to create the values file TEMPERATURE. Remember that each file must have two columns separated by one or more spaces. The left column must contain the station numbers (1-9) while the right column contains the attribute data. When you save each values file, choose Real as the Data Type.

c) When you have finished creating the values files, run REGRESS from the GIS Analysis/Statistics menu. (Because the output of REGRESS is an equation and statistics rather than a data layer, it cannot be implemented in the Macro Modeler.) Indicate that it is a regression between values files. You must specify the names of the files containing the independent and dependent variables. The independent variable will be plotted on the X axis and the dependent variable on the Y axis. The linear equation derived from the regression will give us Y as a function of X. In other words, for any known value of X, the equation can be used to calculate a value for Y. We later want to use this equation to develop a full image of temperature values from our elevation image. Therefore we want to give ELEVATION as the independent variable and TEMPERATURE as the dependent variable. Press OK.

REGRESS will plot a graph of the relationship and its equation. The graph provides us with a variety of information. First, it shows the sample data as a set of point symbols. By reading the X and Y values for each point, we can see the combination of elevation and temperature at each station. The regression trend line shows the "best fit" of a linear relationship to the data at these sample locations. The closer the points are to the trend line, the stronger the relationship. The correlation coefficient ("r") next to the equation tells us the same numerically. If the line is sloping downwards from left to right, "r" will have a negative value indicating a "negative" or "inverse" relationship. This is the case with our data since as elevation increases, temperature decreases. The correlation coefficient can vary from -1.0 (strong negative relationship) to 0 (no relationship) to +1.0 (strong positive relationship). In this case, the correlation coefficient is -0.9652, indicating a very strong inverse relationship between elevation and temperature for these nine locations.

The equation itself is a mathematical expression of the line. In this example, you should have arrived (with rounding) at the following equation:

$$Y = 26.985 - 0.0016 X$$

The equation is that of a line, $Y = a + bX$, where a is the Y axis intercept and b is the slope. X is the independent variable and Y is the dependent variable.

In effect, this equation is saying that you can predict the temperature at any location within this region if you take the elevation in feet, multiply it by -0.0016, and add 26.985 to the result. This then is our "model":

TEMPERATURE = 26.985-0.0016 * [NRELIEF]

d) You may now close the REGRESS display. This model can be evaluated with either SCALAR (in or outside the Macro Modeler) or Image Calculator. In this case, we will use Image Calculator to create TEMPERATURE.[51] Open Image Calculator from the GIS Analysis/Mathematical Operators menu. We will create a Mathematical Expression. Type in TEMPERATURE as the output image name. Tab or click into the Expression to process input box and type in the equation as shown above. When you are ready to enter the filename NRELIEF, you can click the Insert Image button and choose the file from the Pick List. Entering filenames in this manner ensures that square brackets are placed around the filename. When the entire equation has been entered, press Save Expression and give the name TEMPER. (We are saving the expression in case we need to return to this step. If we do, we can simply click Open Expression and run the equation without having to enter it again.) Then click Process Expression.

The resulting image should look very similar to the relief map, except that the values are reversed—high temperatures are found in the Rift Valley, while low temperatures are found in the higher elevations.

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51. If you were evaluating this portion of the model in Macro Modeler, you would need to use SCALAR twice, first to multiply NRELIEF by -0.0016 to produce an output file, then again with that result to add 26.985.

e) To verify this, drag the TEMPERATURE window such that you can see both it and NRELIEF.

Now that we have a temperature map, we need to create the second map required for agro-climatic zoning—a moisture availability map. As stated above, moisture availability can be approximated by dividing the average annual rainfall by the average annual potential evaporation.

We have the rainfall image NRAIN already, but we need to create the evaporation image. The relationship between elevation and potential evaporation has been derived and published by Woodhead (1968, Studies of Potential Evaporation in Kenya, EAAFRO, Nairobi) as follows:

$$E_o(mm) = 2422 - 0.109 * elevation(feet)$$

We can therefore use the relief image to derive the average annual potential evaporation (E_o).

f) As with the earlier equation, we could evaluate this equation using SCALAR or Image Calculator. Again use Image Calculator to create a mathematical expression. Enter EVAPO as the output filename, then enter the following as the expression to process. (Remember that you can press the Insert Image button to bring up a Pick List of files rather than typing in the filename directly.)

2422 - (0.109*[NRELIEF])

Press Save Expression and give the filename MOIST. Then press Process Expression.

g) We now have both of the pieces required to produce a moisture availability map. We will build a model in the Macro Modeler for the rest of the exercise. Open Macro Modeler and place the images NRAIN and EVAPO and the module OVERLAY. Connect the two images to the module, connecting NRAIN first. Right-click on the OVERLAY module and select the Ratio (zero option) operation. Close module parameters then right-click on the output image and call it MOISTAVAIL. Save the model as Exer2-6 then run it.

The resulting image has values that are unitless, since we divided rainfall in mm by potential evaporation which is also in mm. When the result is displayed, examine some of the values using the Cursor Inquiry Mode. The values in MOISTAVAIL indicate the balance between rainfall and evaporation. For example, if a cell has a value of 1.0 in the result, this would indicate that there is an exact balance between rainfall and evaporation.

1 What would a value greater than 1 indicate? What would a value less than 1 indicate?

At this point, we have all the information we need to create our agro-climatic zone (ACZONES) map. The government of Kenya uses the specific classes of temperature and moisture availability that were listed in Table 1 to form zones of varying agricultural suitability. Our next step is therefore to divide our temperature and moisture availability surfaces into these specific classes. We will then find the various combinations that exist for Nakuru District.

h) Place the RECLASS module in the model and connect the input image MOISTAVAIL. Right click on the output image and rename it MOISTZONES. Right click the RECLASS symbol. As we saw in earlier exercises, RECLASS requires a text .rcl file that defines the reclassification thresholds. The easiest way to construct this file is to use the main RECLASS dialog. Close Module Parameters.

Open RECLASS from GIS Analysis/Database Query. There is no need to enter filenames. Just enter the values as shown for moisture zones in Table 1, then press Save as .RCL file. Give the filename MOISTZONES. Then right click to open the RECLASS module parameters in the model and enter MOISTZONES as the .rcl file. Save and run the model.

i) Change the MOISTZONES display to use the IDRISI Default Quantitative palette and equal interval autoscaling.

2 *How many moisture availability zones are in the image? Why is this different from the number of zones given in the table? (If you are having trouble answering this, you may wish to examine the documentation file of MOISTAVAIL.)*

The information we have concerning these zones is published for use in all regions of Kenya. However, our study area is only a small part of Kenya. It is therefore not surprising that some of the zones are not represented in our result.

j) Next we will follow a similar procedure to create the temperature zone map. Before doing so, however, first check the minimum and maximum values in TEMPERATURE to avoid any wasted reclassification steps. Highlight the TEMPERATURE raster layer in the model, then click the Describe icon on the Macro Modeler toolbar. Use Check for the minimum and maximum data values in TEMPERATURE. Then use the main RECLASS dialog again to create an .rcl file called TEMPERZONES with the ranges given in Table 1.

Place another RECLASS model element and rename the output file TEMPERZONES. Link TEMPERATURE as the input file and right-click to open the module parameters. Enter the .rcl file, TEMPERZONES, that you just created.

Now that we have images of temperature zones and moisture availability zones, we can combine these to create agro-climatic zones. Each resulting agro-climatic zone should be the result of a unique combination of temperature zone and moisture zone.

3 *Previously we used OVERLAY to combine two images. Given the criteria for the final image, why can't we use OVERLAY for this final step?*

k) The operation that assigns a new identifier to every distinct combination of input classes is known as cross-classification. In IDRISI, this is provided with the module CROSSTAB. Place the module CROSSTAB into the model. Link TEMPERZONES first and MOISTZONES second. Right-click on the output image and rename it AGROZONES. Then right-click on CROSSTAB to open the module parameters. (Note that the CROSSTAB module when run from the main dialog offers several addition output options that are not available when used in the Macro Modeler.)

The cross-classification image shows all of the combinations of moisture availability and temperature zones in the study area. Notice that the legend for AGROZONES explicitly shows these combinations in the same order as the input image names appear in the title.

Figure 4 shows one way the model could be constructed in Macro Modeler. (Your model should have the same data and command elements, but may be arranged differently.

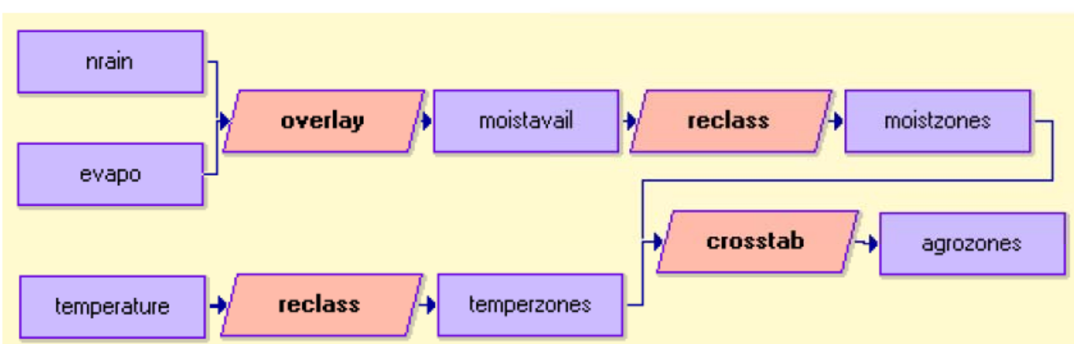

Figure 4

In this exercise, we used Image Calculator and OVERLAY to perform a variety of basic mathematical operations. We used images as variables in evaluating equations, thereby deriving new images. This sort of mathematical modeling (also termed map algebra), in conjunction with database query, form the heart of GIS. We were also introduced to the module CROSSTAB, which creates a new image based on the combination of classes in two input images.

Optional Problem

The agro-climatic zones we have just delineated have been studied by geographers to determine the optimal agricultural activity for each combination. For example, it has been determined that areas suitable for the growing of pyrethrum, a plant cultivated for use in insect repellents, are those defined by combinations of temperature zones 6-8 and moisture availability zones 1-3.

1) Create a map showing the regions suitable for the growth of pyrethrum.

4 *There are several ways to create a map of areas suitable for pyrethrum. Describe how you made your map.*

We will not use any of the images created in this exercise for later exercises, so you may delete them all if you like, except for the original data files NRAIN and NRELIEF.

This completes the GIS tools exercises of the Introductory GIS section of the Tutorial. Database query, distance operators, context operators, and the mathematical operators of map algebra provide the tools you will use again and again in your analyses.

We have made heavy use of the Macro Modeler in these exercises. However, you may find as you are learning the system that the organization of the main menu will help you understand the relationships and common uses for the modules that are listed alphabetically in the Modeler. Therefore, we encourage you to explore the module groupings in the menu as well. In addition, some modules cannot be used in the Modeler (e.g., REGRESS) and others (e.g., CROSSTAB) have additional capabilities when run from the menu.

The remaining exercises in this section concentrate on the role of GIS in decision support, particularly regarding suitability mapping.

Answers

1. The values in MOISTAVAIL are the result of dividing NRAIN by EVAPO. If a value is greater than 1, the NRAIN value was larger than the EVAPO value. This would indicate a positive moisture balance. If a value is less than 1, the NRAIN value was smaller than the EVAPO value. This would indicate a negative moisture balance.

2. Only 5 zones (1-5) are in the image because the range of values is only 0.36 - 1.02 in MOISTAVAIL.

3. We can't use OVERLAY in this situation because we want each unique combination of zones to have a unique value in the output image. With OVERLAY, the combination of temperature zone 2 and moisture zone 4 would give the same result as moisture zone 2 and temperature zone 4.

4. Look at the legend of AGROZONES and determine which classes represent the desired combinations of zones. Use Edit to create a values file to assign those original zone values to the new value 1. Then use ASSIGN with AGROZONES as the feature definition file and the values file created.

Another method is to use Edit/ASSIGN or RECLASS with the zone maps, TEMPERZONES and MOISTZONES, creating Boolean images representing only those zones suitable for pyrethrum. These two Boolean images could then be multiplied with OVERLAY to produce the final result.

Exercise 2-7
MCE: Criteria Development and the Boolean Approach

The next five exercises will explore the use of GIS as a decision support system. Although techniques will be discussed that can enhance many types of decision making processes, the emphasis will be placed on the use of GIS for suitability mapping and resource allocation decisions. These decisions are greatly assisted by GIS tools because they often involve a variety of criteria that can be represented as layers of geographic data. Multi-criteria evaluation (MCE) is a common method for assessing and aggregating many criteria. However, its full potential is only recently being realized.

An important first step in understanding MCE is to develop a common language in which to present and approach such methods. If the reader has not already done so, the chapter on **Decision Support: Decision Strategy Analysis** in the **IDRISI Guide to GIS and Image Processing** should be reviewed. The language presented there will be used in these exercises.

In this next set of exercises we will explore a variety of MCE techniques. In this exercise, criteria will be developed and standardized, and a simple Boolean aggregation method will be used to arrive at a solution. The following two exercises explore more flexible and sophisticated aggregation methods. Exercise 2-8 illustrates the use of the Weighted Linear Combination (WLC), while Exercise 2-9 introduces the Ordered Weighted Averaging (OWA) aggregation technique. Exercise 2-10 addresses issues of site selection, particularly regarding spatial contiguity and minimum site area requirements.The final exercise in this set, Exercise 2-11, expands the problem to include more than one objective and uses multi-objective allocation procedures to produce a final solution.

Often, some of the data layers developed in an exercise will be used in subsequent exercises. At the end of each exercise, you will be told which layers must be kept. However, if possible, you may wish to keep all the data layers you develop for this set of exercises to facilitate further independent exploration of the techniques presented.

To demonstrate the different ways criteria can be developed, as well as the variety of MCE procedures available, the first four exercises of this series will concentrate on a single hypothetical suitability problem. The objective is to find the most suitable areas for residential development in the town of Westborough, Massachusetts, USA. The town is located very near two large metropolitan areas and is a prime location for residential (semi-rural) development.

a) Change your Working Folder to the IDRISI Tutorial\MCE folder using IDRISI Explorer.

b) Display the image MCELANDUSE using the user-defined MCELANDUSE palette. Choose to display the legend and title map components. Use Add Layer to add the streams layer MCESTREAMS with the user-defined BLUE symbol file and the roads layer MCEROADS with the default Outline Black symbol file.

   As you can see, the town of Westborough and its immediate vicinity are quite diverse. The use of GIS will make the identification of suitable lands more manageable.

Because of the prime location, developers have been heavily courting the town administrators in an effort to have areas that best suit their needs allocated for residential development. However, environmental groups also have some influence on where new development will or will not occur. The environmentally-mixed landscape of Westborough includes many areas that should be preserved as open space and for wildlife. Finally, the town of Westborough has some specific regulations already in place that will limit land for development. All these considerations must be incorporated into the decision making process.

This problem fits well into an MCE scenario. The goal is to explore potential suitable areas for residential development for the town of Westborough: areas that best meet the needs of all groups involved. The town administrators are collaborating with both developers and environmentalists and together they have identified several criteria that will assist in the decision making process. This is the first step in the MCE process, identifying and developing criteria.

Original Data and Criteria Development

In order to determine which lands to consider for development, the town administration has identified three sets of criteria: town regulations that limit where development can occur, financial considerations important to developers, and wildlife considerations important to environmentalists. In this problem, all criteria will be expressed as raster images.

Criteria are of two types, constraints and factors. Constraints are those Boolean criteria that constrain (i.e., limit) our analysis to particular geographic regions. No matter which method is eventually used to aggregate criteria, constraints are always Boolean images. In this case, the constraints differentiate areas that we can consider suitable for residential development from those that cannot be considered suitable under any conditions.

In contrast, factors are criteria that define some degree of suitability for all geographic regions. They define areas or alternatives in terms of a continuous measure of suitability. Individual factor scores may either enhance (with high scores) or detract from (with low scores) the overall suitability of an alternative. (The degree to which this happens depends upon the aggregation method used.) Factors can be standardized in a number of ways depending upon the individual criteria and the form of aggregation eventually used.

In our example, we have two constraints and six factors that will be developed. We will now turn our attention to the development of these criteria.

Note: Many of the tools needed to develop the initial criteria layers of this exercise were presented in earlier exercises. To move more quickly to the new concepts of these exercises, the initial criteria layers are provided. The data used to derive these initial images in this section are included in the compressed supplemental file called MCESUPPLEMENTAL.ZIP. If desired, you can uncompress and use these files to practice the initial stages of criteria development. The methods needed were introduced in Exercises 2-2 through 2-5.

Constraints

The town's building regulations are constraints that limit the areas available for development. Let's assume new development cannot occur within 50 meters of open water bodies, streams, and wetlands.

c) Display the image MCEWATER with the IDRISI Default Qualitative palette.

To create this image, information about open water bodies, streams, and wetlands was brought into the database. The open water data was extracted from the landuse map, MCELANDUSE. The streams data came from a USGS DLG file that was imported then rasterized. The wetlands data used here were developed from classification of a SPOT satellite image. These three layers were combined to produce the resultant map of all water bodies, MCEWATER.[48]

d) Display the image WATERCON with the IDRISI Default Qualitative palette.

This is a Boolean image of the 50 m buffer zone of protected areas around the features in MCEWATER. Areas that should not be considered are given the value 0 while those that should be considered are given the value 1. When the constraints are multiplied with the suitability map, areas that are constrained are *masked out* (i.e., set to 0), while those that are

48. The wetlands data is in the image MCEWETLAND in MCESUPPLEMENTAL.ZIP. The streams data is the vector file MCESTREAMS we used earlier in this exercise.

not constrained retain their suitability scores.

In addition to the legal constraint developed above, new residential development will be constrained by current landuse; new development cannot occur on already developed land.

e) Look at MCELANDUSE again. (You can quickly bring any image to focus by choosing it from the Window List menu.) Clearly some of these categories will be unavailable for residential development. Areas that are already developed, water bodies, and large transportation corridors cannot be considered suitable to any degree.

f) Display LANDCON, a Boolean image produced from MCELANDUSE such that areas that are suitable have a value of 1 and areas that are unsuitable for residential development have a value of 0.[49]

Now we will turn our attention to the continuous factor maps. Of the following six factors, the first four are relevant to building costs while the latter two concern wildlife habitat preservation.

Factors

Having determined the constraining criteria, the more challenging process for the administrators was to identify the criteria that would determine the *relative* suitability of the remaining areas. These criteria do not absolutely constrain development, but are factors that enhance or detract from the relative suitability of an area for residential development.

For developers, these criteria are factors that determine the cost of building new houses and the attractiveness of those houses to purchasers. The feasibility of new residential development is determined by factors such as current landuse type, distance from roads, slopes, and distance from the town center. The cost of new development will be lowest on land that is inexpensive to clear for housing, near to roads, and on low slopes. In addition, building costs might be offset by higher house values closer to the town center, an area attractive to new home buyers.

The first factor, that relating the current landuse to the cost of clearing land, is essentially already developed in the MCELANDUSE image. All that remains is to transform the landuse category values into suitability scores. This will be addressed in the next section.

The second factor, distance from roads, is represented with the image ROADDIST. This is an image of simple linear distance from all roads in the study area. This image was derived by rasterizing and using the module DISTANCE with the vector file of roads for Westborough.

The image TOWNDIST, the third factor, is a cost distance surface that can be used to calculate travel time from the town center. It was derived from two vector files, the roads vector file and a vector file outlining the town center.

The final factor related to developers' financial concerns is slope. The image SLOPES was derived from an elevation model of Westborough.[50]

g) Examine the images ROADDIST, TOWNDIST, and SLOPES using the IDRISI Default Qualitative palette. Display MCELANDUSE with the IDRISI Default Qualitative palette.

    1 *What are the values units for each of these continuous factors? Are they comparable?*

    2 *Can categorical data (such as landuse) be thought of in terms of continuous suitability? How?*

While the factors above are important to developers, there are other factors to be considered, namely those important to

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49. MCELANDUSE categores 1-4 are considered suitable and categories 5-13 are constrained.

50. MCEROAD, a vector file of roads; MCECENTER, a vector file showing the town center; and MCEELEV, an image of elevation, can all be found in the compressed file MCESUPPLEMENTAL. The cost-distance calculation used the cost grow option and a friction surface where roads had a value of 1 and off-road areas had a value of 3.

environmentalists.

Environmentalists are concerned about groundwater contamination from septic systems and other residential non-point source pollution. Although we do not have data for groundwater, we can use open water, wetlands, and streams as surrogates (i.e., the image MCEWATER). Distance from these features has been calculated and can be found in the image WATERDIST. Note that a buffer zone of 50 meters around the same features was considered an absolute constraint above. This does not preclude also using distance from these features as a factor in an attempt by environmentalists to locate new development even further from such sensitive areas (i.e., development MUST be at least 50 meters from water, but the further the better).

The last factor to be considered is distance from already-developed areas. Environmentalists would like to see new residential development near currently-developed land. This would maximize open land in the town and retain areas that are good for wildlife distant from any development. Distance from developed areas, DEVELOPDIST, was created from the original landuse image.

h) Examine the images WATERDIST and DEVELOPDIST using the IDRISI Default Qualitative palette.

3 What are the values units for each of these continuous factors? Are they comparable with each other?

We now have the eight images that represent criteria to be standardized and aggregated using a variety of MCE approaches. The Boolean approach is presented in this exercise while the following two exercises address other approaches. Regardless of the approach used, the objective is to create a final image of suitability for residential development.

The Boolean Approach

The first method that will be used to solve this MCE problem is the familiar Boolean approach. All criteria (constraints and factors) will be standardized to Boolean values (0 and 1) and the method of aggregation will be Boolean intersection (multiplication of criteria). This is the most common GIS method of multiple criteria evaluation and it has been used extensively in previous exercises (e.g., 2-2 and 2-3). While this technique is common, we shall see that Boolean standardization and aggregation severely limit analysis and constrain resultant land allocation choices. Subsequent exercises will explore other approaches.

Boolean Standardization of Factors

While it is clearly appropriate that constraints be expressed in Boolean terms, it is not always clear how continuous data (e.g., slopes) can be effectively reduced to Boolean values. However, the logic of Boolean aggregation demands all criteria (constraints and factors) be standardized to the same Boolean scale of 0 or 1. All of the continuous factors developed above must be reduced to Boolean constraints as in previous exercises. For each factor, a "crisp" or "hard" decision as to what defines suitable areas for development must be made. The following are the decision rules for each factor.

Landuse Factor

Of the four landuse types available for development, forested and open undeveloped lands are the least expensive and will be considered equally suitable by developers, while all other land will be considered completely unsuitable. Note that this factor, expressed as a Boolean constraint, will make redundant the landuse constraint developed earlier. In later exercises, this will not be the case.

i) Display a Boolean image called LANDBOOL. It was created from the landuse map MCELANDUSE using the RECLASS module. In the LANDBOOL image, suitable areas have a value of 1 and unsuitable areas have a value of 0.

Distance from Roads Factor

To keep costs of development down, areas closer to roads are considered more suitable than those that are distant. However, for a Boolean analysis we need to reclassify our continuous image of distance from roads to a Boolean expression of distances that are suitable and distances that are not suitable. We will reclassify our image of distance from roads such that areas less than 400 meters from any road are suitable and those equal to or beyond 400 meters are not suitable.

j) Display a Boolean image called ROADBOOL. It was created using RECLASS with the continuous distance image, ROADDIST. In this image, areas within 400 meters of a road have a value of 1 and those beyond 400 meters have a value of 0.

Distance to Town Center Factor

Homes built close to the town center will yield higher revenue for developers. Distance from the town center is a function of travel time on area roads (or potential access roads) which was calculated using a cost distance function. Since developers are most interested in those areas that are within 10 minutes driving time of the town center, we have approximated that this is equivalent to 400 grid cell equivalents (GCEs) in the cost distance image. We reclassified the cost distance surface such that any location is suitable if it is less than 10 minutes or 400 GCEs of the town center. Those 400 GCEs or beyond are not suitable.

k) Display a Boolean image called TOWNBOOL. It was created from the cost distance image TOWNDIST. In the new image, a value of 1 is given to areas within 10 minutes of the town center.

Slope Factor

Because relatively low slopes make housing and road construction less expensive, we reclassified our slope image so that those areas with a slope less than 15% are considered suitable and those equal to or greater than 15% are considered unsuitable.

l) Display a Boolean image called SLOPEBOOL. It was created from the slope image SLOPES.

Distance from Water Factor

Because local groundwater is at risk from septic system pollution and runoff, environmentalists have pointed out that areas further from water bodies and wetlands are more suitable than those that are nearby. Although these areas are already protected by a 50 meter buffer, environmentalists would like to see this extended another 50 meters. In this case, suitable areas will have to be at least 100 meters from any water body or wetland.

m) Display a Boolean image called WATERBOOL. It was created from the distance image called WATERDIST. In the Boolean image, suitable areas have a value of 1.

Distance from Developed Land Factor

Finally, areas less than 300 meters from developed land are considered best for new development by environmentalists interested in preserving open space.

n) Display a Boolean image called DEVELOPBOOL. It was created from DEVELOPDIST by assigning a value of 1 to areas less than 300 meters from developed land.

Boolean Aggregation of Factors and Constraints

Now that all of our factors have been transformed into Boolean images (i.e., reduced to constraints), we are ready to aggregate them. In the most typical Boolean aggregation procedure, all eight images are multiplied together to produce a single image of suitability. This procedure is equivalent to a logical AND operation and can be accomplished in several ways in IDRISI, (e.g., using the Decision Wizard, the MCE module, a series of OVERLAY multiply operations, or Image Calculator with a logical expression multiplying all the images).

In assessing the results of an MCE analysis, it is very helpful to compare the resultant image to the original criteria images. This is most easily accomplished by identifying the images as parts of a group, then using the Feature Properties query tool from the toolbar in any one of them.

o) Open the DISPLAY Launcher dialog box and invoke the Pick List. You should see the filename MCEBOOL-GROUP in the list with a small plus sign next to it. This is an image group file that has already been created using IDRISI Explorer. Click on the plus sign to see a list of the files that are in the group. Choose MCEBOOL and press OK. Note that the filename shown in the DISPLAY Launcher input box is MCEBOOL-GROUP.MCEBOOL. Choose the IDRISI Default Qualitative palette and click OK to display MCEBOOL.[51]

p) Use the Feature Properties query tool (from its toolbar icon or Composer button) and explore the MCEBOOL-GROUP. Click on the image to check the values in the final image and in the eight criterion images. The Feature Properties display may be repositioned by dragging.

4 *What must be true of* all criterion images *for MCEBOOL to have a value 1? Is there any indication in MCEBOOL of how many criteria were met in any other case?*

5 *For those areas with the value 1, is there any indication which were better than others in terms of distance from roads, etc.? If more suitable land has been identified than is required, how would one now choose between the alternatives of suitable areas for development?*

Assessing the Boolean Approach

Tradeoff and Risk

It should have been clear that a value of 1 in the final suitability image is only possible where all eight criteria also have a value of 1, and a value of 0 is the result if even one criterion has a value of 0. In this case, suitability in one criteria cannot compensate for a lack of suitability in any other. In other words, they do not *trade off*. In addition, because the Boolean multi-criteria analysis is a logical AND (minimum) operation, in terms of *risk*, it is very conservative. Only by exactly meeting all criteria is a location considered suitable. The result is the best location possible for residential development and no less suitable locations are identified.

These properties of no tradeoff and risk aversion may be appropriate for many projects. However, in our case, we can imagine that our criteria should compensate for each other. We are not just interested in extreme risk aversion. For example, a location far from the town center (not suitable when considering this one criteria) might be an excellent location in all other respects. Even though it may not be the most suitable location, we may want to consider it suitable to some degree.

On the other end of the risk continuum is the Boolean OR (maximum) aggregation method. Whereas the Boolean AND require all criteria to be met for an area to be called suitable, the Boolean OR requires that at least one criteria be met. This is clearly quite risky because for any suitable area, all but one criteria could be unacceptable.

q) Display the BOOLOR image using the IDRISI Default Qualitative palette. It was created using the logical OR operation in Image Calculator. You can see that almost the entire image is mapped as suitable when the Boolean OR aggregation is used.

6 *Describe BOOLOR. Can you think of a way to use the Boolean factors to create a suitability image that lies somewhere between the extremes of AND and OR in terms of risk?*

The exercises that follow will use other standardization and aggregation procedures that will allow us to alter the level of

51. The interactive tools for group files (Group Link and Feature Properties query) are only available when the image(s) have been displayed as members of the group, with the full dot logic name. If you display MCEBOOL without its group reference, it will not be recognized as a group member.

both tradeoff and risk. The results will be images of continuous suitability rather than strict Boolean images of absolute suitability or non-suitability.

Criterion Importance

Another limitation of the simple Boolean approach we used here is that all factors have equal importance in the final suitability map. This is not likely to be the case. Some criteria may be very important to determining the overall suitability for an area while others may be of only marginal importance. This limitation can be overcome by weighting the factors and aggregating them with a weighted linear average or WLC. The weights assigned govern the degree to which a factor can compensate for another factor. While this could be done with the Boolean images we produced, we will leave the exploration of the WLC method for the next exercise.

Spatial Contiguity and Site Size

The Boolean multi-criteria result shows all locations that are suitable given the criteria developed above. However, it should be clear that suitable areas are not always contiguous and are often scattered in a fragmented pattern. For problems such as residential development site selection, suitable but small sites are not appropriate. This problem of contiguity can be addressed by adding a post-aggregation constraint such as "suitable areas must also be at least 20 hectares size." This constraint would be applied after all suitable locations (of any size) are found. For more information on post-aggregation constraints for site selection, please refer to Exercise 2-10.

Do not delete any images used or created in this exercise. They will be used in the following exercises.

Answers

1. Use Metadata in IDRISI Explorer to access the documentation file for the images and look at the Value Units fields. ROADDIST values are in meters. TOWNDIST values are in units of cost-distance called Grid Cell Equivalents (GCE). SLOPES values are in percent. They are not directly comparable, i.e., we don't know how a value of 10 meters from the road compares with a value of 4 degrees slope.

2. The categorical landuse image does not represent a spatially continuous variable. However, the relative suitability of each landuse type for the objective being considered could be considered to be continuous, ranging from no suitability to perfectly suitable. Each landuse type in the study area could be located on this suitability continuum.

3. Both are in meters, so in terms of distance they are comparable with each other. However, they may not be any more comparable in terms of suitability than the previous factors discussed. For example, 100 meters from water may represent a very high suitability for that criteria while the same distance from developed areas might represent only marginal suitability on that criteria.

4. All criterion images must have the value 1 for MCEBOOL to have the value 1. In the group query, one can tell how many criteria met or failed. The aggregate image itself (MCEBOOL), however, carries no information to distinguish between pixels for which all criteria are unsuitable and those for which all but one criteria were suitable.

5. All the information about the degree of suitability within the Boolean suitable area is lost. Because of this, there is no information to guide the choice of a final set of areas from all the areas described as suitable. Further analysis would have to be performed.

6. Almost the entire image is mapped as suitable when the Boolean OR aggregation is used. One might think of several ways to achieve a solution between AND and OR. For example, it would be possible to require 4 criteria to be met. This could be evaluated by adding all the Boolean images, then reclassifying to keep those areas with value 4 or higher. However, the hard and arbitrary nature of the Boolean standardization limits the flexibility and utility of any approach using these images.

Exercise 2-8
MCE: Non-Boolean Standardization and Weighted Linear Combination

The following exercise builds upon concepts discussed in the **Decision Support: Decision Strategy Analysis** chapter of the **IDRISI Guide to GIS and Image Processing** as well as Exercise 2-7 of the Tutorial. This exercise introduces a second method of standardization in which factors are not reduced to simple Boolean constraints. Instead, they are standardized to a continuous scale of suitability from 0 (the least suitable) to 255 (the most suitable). Rescaling our factors to a standard continuous scale allows us to compare and combine them, as in the Boolean case. However, we will avoid the hard Boolean decision of defining any particular location as absolutely suitable or not for a given criteria. In this exercise we will use a soft or "fuzzy" concept to give all locations a value representing its degree of suitability. Our constraints, however, will retain their "hard" Boolean character.

We will also use a different aggregation method, the Weighted Linear Combination (WLC). This aggregation procedure not only allows us to retain the variability from our continuous factors, it also gives us the ability to have our factors trade off with each other. A low suitability score in one factor for any given location can be compensated for by a high suitability score in another factor. How factors tradeoff with each other will be determined by a set of Factor Weights that indicate the relative importance of each factor. In addition, this aggregation procedure moves the analysis well away from the extreme risk aversion of the Boolean AND operation. As we will see, WLC is an averaging technique that places our analysis exactly halfway between the AND (minimum) and OR (maximum) operations, i.e., neither extreme risk aversion nor extreme risk taking.

a) Start the Decision Wizard by selecting it from the GIS Analysis/Decision Support menu.

The Wizard is meant to facilitate your use of the decision support modules FUZZY, MCE, WEIGHT, RANK and MOLA, each of which may be run independently. We encourage you to become familiar with the main interfaces of these modules as well as with their use in the Wizard. Each Wizard screen asks you to enter specific pieces of information to build up a full decision support model. After entering all the information requested on a Wizard page, click the Next button to move to the next step. The information that you enter on each screen is saved whenever you move to the next screen. The Save As button allows you to save the current model under a different name.

b) **Introduction**. While you are becoming familiar with the Wizard, take time to read both the information presented on each screen and its accompanying Help page. When you have finished reading, click the Next button.

c) **Specify Decision Wizard File**. Open an existing Decision Wizard file called WLC. This Decision Wizard file has all model parameters specified and saved. In this exercise, we will walk through each step of the model. In subsequent exercises we will see how changing certain model parameters affects the model result. Click the Next button to move to the next step. When you get a warning about saving the file, click OK.

d) **Specify Objectives**. This model has one objective called Residential. Click Next to proceed to the next screen.

e) **Definition of Criteria**. Click Next.

f) **Specify Constraints**. This model has two constraints, LANDCON and WATERCON. Note that these images were constructed outside of the Wizard (as described in the previous exercise) and the filenames are simply entered here. Click Next.

g) **Specify Factors**. Note that the six images used in the previous exercise to create the Boolean factor images are each listed here. Standardization of continuous factors is accomplished with the module FUZZY and is facilitated through the Decision Wizard.

Standardization of Factors to a Continuous Scale

The standardization procedure for WLC is somewhat more involved than in the Boolean case. Factors are not just reclassified into 0's and 1's, but are rescaled to a particular common range according to some function. In order to use fuzzy factors with the multi-criteria evaluation, these factors will be standardized to a byte-level range of 0 - 255.[48] The original constraints in our example, water bodies and wetlands (WATERCON) and certain landuse categories (LANDCON), will remain as Boolean images (i.e., constraining criteria) that will simply act as masks in the last step of the WLC.

Let us reconsider our original factors, standardization guidelines, and decision rules. These decision rules were previously in the form of hard decisions. Our factors were reduced to Boolean constraints using crisp set membership functions, 0's and 1's. Now our factors will be considered in terms of fuzzy decision rules where suitable and unsuitable areas are continuous measures. The resulting continuous factors to be produced below will be developed using fuzzy set membership functions.[49]

Landuse Factor

In our Boolean MCE, we reclassified our landuse types available for development into suitable (Forest and Open Undeveloped) and unsuitable (all other landuse categories) (LANDBOOL). However, according to developers, there are four landuse types that are suitable to some degree (Forested Land, Open Undeveloped Land, Pasture, and Cropland), each with a different level of suitability for residential development. Knowing the relative suitability of each category, we can rescale them into the range 0-255. While most factors can be automatically rescaled using some mathematical function, rescaling categorical data such as landuse simply requires giving a rating to each category based on some knowledge. In this case, the suitability rating is specified by developers.

h) Creating a quantitative factor from a qualitative input image must be done outside the Wizard. In this case Edit/ASSIGN was used to give each landuse category a suitability value. Display the image called LANDFUZZ. It is a standardized factor map derived from the image MCELANDUSE. On the continuous (i.e., fuzzy) 0-255 scale we gave a suitability rating of 255 to Forested Land, 200 to Open Undeveloped land, 125 to areas under Pasture, 75 to Cropland, and gave all other categories a value of 0.

i) Now return to the Decision Wizard. The first factor listed is LANDFUZZ. Since it is already standardized, it reads No in the FUZZY column, and the output factor file is the same as the input file. All the other factors need to be standardized using the FUZZY module (notice that it reads Yes in the FUZZY and output filename columns). Click Next.

j) **FUZZY Factor Standardization**. Standardization is necessary to transform the disparate measurement units of the factor images into comparable suitability values. The selection of parameters for this standardization relies upon the user's knowledge of how suitability changes for each factor. The Wizard will present a screen for each factor to be standardized. The factor name is shown, along with the minimum and maximum data values for the input image. A fuzzy membership function shape and type must be specified. A generic figure illustrating the chosen function is shown (i.e., the figure is not specific to the values you enter). Control point values are entered. Below is a description of the standardization criteria used with each factor image.

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48. The 0-255 range provides the maximum differentiation possible with the byte data type.

49. See the **Decision Support: Decision Strategy Analysis** chapter of the **IDRISI Guide to GIS and Image Processing** for a detailed discussion of fuzzy set membership functions.

Distance to Town Center Factor

The simplest rescaling function for continuous data takes an original range of data and performs a simple linear stretch. For example, measures of relative distance from the town center, an important determinant of profit for developers, will be rescaled to a range of suitability where the greatest cost distance has the lowest suitability score (0) and the least cost distance has the highest suitability score (255). A simple linear distance decay function is appropriate for this criteria, i.e., as cost distance from the town center increases, its suitability decreases.

To rescale the cost distance factor, we chose the monotonically decreasing linear function (pictured on the screen) and used minimum (0) and maximum (582) distance values found in our cost distance image as the control points at the end of the linear curve.

k) Click the Next button to move to the next step.

Distance to Open Water Factor

Other factors, such as our distance from water bodies, do not have a constant decrease or increase in suitability based solely on distance. We know, for example, that town regulations require residential development to be at least 50 meters from open water and wetlands, and environmentalists prefer to see residential development even further from these water bodies. However, a distance of 800 meters might be just as good as a distance of 1000 meters. Suitability may not increase with distance in a constant fashion.

In our case study, suitability is very low within 100 meters of water. Beyond 100 meters, all parties agree that suitability increases with distance. However, environmentalists point out that the benefits of distance level off to maximum suitability at approximately 800 meters. Beyond 800 meters, suitability is again equal. This function cannot be described by the simple linear function used in the preceding factor. It is best described by an increasing Sigmoidal curve.

l) We used a monotonically increasing Sigmoidal function to rescale the values in the distance-from-water image WATERDIST. Notice that the name of this factor is highlighted in the list in the upper right corner of the screen. To accommodate the two thresholds of 100 and 800 meters in our function, the control points are no longer the minimum and maximum of our input values. Rather, they are equivalent to the points of inflection on the Sigmoidal curve. In the case of an increasing function, the first control point (a) is the value at which suitability begins to rise sharply above zero and the second control point (b) is the value at which suitability begins to level off and approaches a maximum of 255. Therefore, for this factor, input a value of 100 for control point a and a value of 800 for control point b.

m) Click the Next button to move to the next factor.

Distance to Roads Factor

Similar to our distance from water factor, distance from roads is a continuous factor to be rescaled to the byte range 0-255. In the previous exercise, developers identified only areas within 400 meters of roads as suitable. However, given the ability to determine a range of suitability, they have identified areas within 50 meters of roads as the most suitable and areas beyond 50 meters as having a continuously decreasing suitability that approaches, but never reaches 0. This function is adequately described by a decreasing J-shaped curve.

n) To rescale our distance from roads factor to this J-shaped curve, we chose a monotonically decreasing function. As with the other functions, the first control point is the value at which the suitability begins to decline from maximum suitability. However, because the J-shaped function never reaches 0, the second control point is set at the value at which suitability is halfway between not suitable and perfectly suitable. We used 50 for the value of the first control point (c) and 400 for the value of the second control point (d).

o) Click the Next button to move to the next step.

Slopes Factor

We know from our discussion in the previous exercise that slopes below 15% are the most cost effective for development. However, the lowest slopes are the best and any slope above 15% is equally unsuitable. We again used a monotonically decreasing sigmoidal function to rescale our data to the 0-255 range.

p) Click the Next button to move to the next step.

Distance from Developed Land Factor

Finally, our last factor, distance from developed land, is also rescaled using a linear distance decay function. Areas closer to currently developed land are more suitable than areas farther from developed land, i.e., suitability decreases with distance.

q) The minimum distance value in the image is the first control point (0) and the maximum (1324.4) is the second.

All factors have now been standardized to the same continuous scale of suitability (0-255). Standardization makes comparable factors representing different criteria measured in different ways. This will also allow us to combine or aggregate all the factor images.

r) Click the Next button. Each standardized factor image will be automatically displayed. If FUZZY standardization is required, FUZZY will run, then the standardized factor image will display. After all the factors are standardized, the next screen is displayed.

Weighting Factors for Aggregation

One of the advantages of the WLC method is the ability to give different relative weights to each of our factors in the aggregation process. Factor weights, sometimes called tradeoff weights, are assigned to each factor. They indicate a factor's importance relative to all other factors and they control how factors will tradeoff or compensate for each other. In the case of WLC, where factors fully tradeoff, factors with high suitability in a given location can compensate for other factors with low suitability in the same location. The degree to which one factor can compensate for another is determined by its factor or tradeoff weight.

In IDRISI, the module WEIGHT utilizes a pairwise comparison technique to help you develop a set of factor weights that will sum to 1.0. Factors are compared two at a time in terms of their importance relative to the stated objective (e.g., locating residential development). After all possible combinations of two factors are compared, the module calculates a set of weights and, importantly, a consistency ratio. The ratio indicates any inconsistencies that may have been made during the pairwise comparison process. The module allows for repeated adjustments to the pairwise comparisons and reports the new weights and consistency ratio for each iteration.

s) **Choose Factor Weighting Option**. Choose the AHP (Analytical Hierarchy Process) option to derive the weights (note that this is not the default—you must choose it). Click the Next button. This launches the module WEIGHT. Choose to use a previous pairwise comparison file (.pcf) and select the file RESIDENTIAL. Also specify that you wish to produce an output decision support file and type in the same name, RESIDENTIAL. Then press the Next button.

The second WEIGHT dialog box displays a pairwise comparison matrix that contains the information stored in the .pcf file RESIDENTIAL. This matrix indicates the relative importance of any one factor relative to all others. It is the hypothetical result of lengthy discussions amongst town planners and their constituents. To interpret the matrix, ask the question, "Relative to the column factor, how important is the row factor?" Answers are located on the 9-point scale shown at the top of the WEIGHT dialog. For example, relative to being near the town (TOWNFUZZ), being near to roads (ROADFUZZ) is very strongly more important (a matrix value of 7) and compared to being on low slopes (SLOPEFUZZ), being near developed areas (DEVELOPFUZZ) is strongly less important. Take a few moments to assess the relative importance assigned to each factor.[50] Press the OK button and choose to overwrite the file if prompted.

The weights derived from the pairwise comparison matrix are displayed in the Module Results box. These weights are also written to the decision support file RESIDENTIAL. The higher the weight, the more important the factor in determining suitability for the objective.

1 *What are the weights for each factor? Do these weights favor the concerns of developers or environmentalists?*

We will choose to use the pairwise comparison matrix as it was developed. (You can return to WEIGHT later to explore the effect of altering any of the pairwise comparisons.)

The WEIGHT module is designed to simplify the development of weights by allowing the decision makers to concentrate on the relative importance of only two factors at a time. This focuses discussion and provides an organizational framework for working through the complex relationships of multiple criteria. The weights derived through the module WEIGHT will always sum to 1. It is also possible to develop weights using any method and use these with MCE-WLC, so long as they sum to 1.

2 *Give an example from everyday life when you consciously weighted several criteria to come to a decision (e.g., selecting a particular item in a market, choosing which route to take to a destination). Was it difficult to consider all the criteria at once?*

t) Close the WEIGHT module results dialog by clicking Close. This returns you to the Wizard. Click the Retrieve AHP weights button and choose the RESIDENTIAL.DSF file just created with WEIGHT. The factor weights will appear in the table. Click the Next button.

Aggregating Weighted Factors and Constraints using WLC

One of the most common procedures for aggregating data is by Weighted Linear Combination (WLC). With WLC, each standardized factor is multiplied by its corresponding weight, these are summed, and then the sum is divided by the number of factors. Once this weighted average is calculated for each pixel, the resultant image is multiplied by the relevant Boolean constraints (in our example, LANDCON and WATERCON) to mask out areas that should not be considered at all. The final image is a measure of aggregate suitability that ranges 0-255 for non-constrained locations.

u) **Ordered Weighted Averaging (OWA).** Choose the No OWA option (we will return to OWA in the next exercise) and click the Next button.

v) **Objective Summary and Output MCE Filename.** You will be presented with a summary of the decision rule for the multi-criteria model for residential development. Click on each of the three model component buttons to see all the settings. Call the output image MCEWLC (this is not the default) and click the Next button. The module MCE will run and the final aggregated suitability image is automatically displayed. Click on the Finish button and close the Wizard.

We will explore the resulting aggregate suitability image with the Feature Properties tool to better understand the origin of

50. It is with much difficulty that factors relevant to environmentalists have been measured against factors relevant to developers' costs. For example, how can an environmental concern for open space be compared to and eventually tradeoff with costs of development due to slope? We will address this issue directly in the next exercise.

the final values.

w) Under the Window List menu, choose Close All Windows. Use DISPLAY Launcher to access the Pick List. Find the group file MCEWLC in the Pick List and open it by clicking on the plus sign. (This was created using IDRISI Explorer.) Choose MCEWLC and display it with the IDRISI Default Quantitative palette. Use the Feature Properties query tool to explore the values in the image. The values are more quickly interpreted if you choose the View as Graph option on the Feature Properties dialog, select Relative Scaling and set the graph limit endpoints to be 0 and 255.[51]

It should be clear from your exploration that areas of similar suitability do not necessarily have the same combination of suitability scores for each factor. Factors tradeoff with each other throughout the image.

3 Which two factors most determine the character of the resulting suitability map? Why?

The MCEWLC result is a continuous image that contains a wealth of information concerning overall suitability for every location. However, using this result for site selection is not always obvious. Refer to Exercise 2-10 for site selection methods relevant to continuous suitability images. You may now delete the unstandardized factor images (MCELANDUSE, TOWNDIST, WATERDIST, ROADDIST, SLOPES, DEVELOPDIST) if you need space on your hard drive. Save all other images used or created in this exercise for use in the following exercises.

Assessing the WLC Approach

The WLC procedure allows full tradeoff among all factors. However, the amount any single factor can compensate for another is determined by its factor weight. In our example, a high suitability score in SLOPEFUZZ can easily compensate for a low suitability score in LANDFUZZ for the same location. In the resultant image that location will have a high suitability score. In the reverse scenario, a high suitability score in LANDFUZZ can only weakly compensate for a low score in SLOPEFUZZ. It can tradeoff, but the degree to which it will impact the final result is severely limited by the low factor weight of LANDFUZZ.

In terms of relative risk, we saw earlier how a Boolean MCE that uses the AND operation is essentially a very conservative or risk averse operation, and that the OR operation is extremely risk taking. These are the extremes on a continuum of risk. WLC lies exactly in the middle of this continuum. WLC, then, is characterized by full tradeoff and average risk as illustrated by Figure 1.

51. See the on-line Help System for Feature Properties for more information about these options.

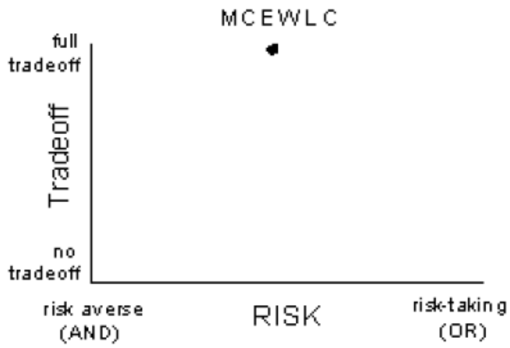


Figure 1

The weighted linear combination aggregation method offers much more flexibility than the Boolean approaches of the previous exercise. It allows for criteria to be standardized in a continuous fashion, retaining important information about degrees of suitability. It also allows the criteria to be differentially weighted and to trade off with each other. In the next exercise, we will explore another aggregation technique, ordered weighted averaging (OWA), that will allow us to control the amount of risk and tradeoff we wish to include in the result.

Answers

1. The factor weights are listed below. Those of concern to the developers are assigned the bulk of the weight. The weights of the two environmental factors, distance from development and distance from water, sum to 0.2158 while those of the other factors sum to 0.7842.

developfuzz	0.1085
slopefuzz	0.3171
landfuzz	0.0620
townfuzz	0.0869
waterfuzz	0.1073
roadfuzz	0.3182

2. Answers will vary. One common decision is in which route to take when trying to get somewhere. One might consider the time each potential route would take, the quality of the scenery, the costs involved, and whether an ice cream stand can be found along the way.

3. Slope gradient and distance from roads are both strong determinants of suitability in the final map. This is because the weights for those two factors are much higher than for any other.

Exercise 2-9
MCE: Ordered Weighted Averaging

In this exercise, we will explore Ordered Weighted Averaging (OWA) as a method for MCE. This technique, like WLC, is best used with factors that have been standardized to a continuous scale of suitability and weighted according to their relative importance. Constraints will remain as Boolean masks. Therefore, this exercise will simply use the constraints, standardized continuous factors, and weights developed in the previous exercises. However, in the case of OWA, a second set of weights, Order Weights, will also be applied to the factors. This will allow us to control the overall level of tradeoff between factors, as well as the level of risk in our suitability determination.

Our first method of aggregation, Boolean, demanded that we reduce our factors to simple constraints that represent "hard" decisions about suitability. The final map of suitability for residential development was the product of the logical AND (minimum) operation, i.e., it was a risk-averse solution that left no possibility for criteria to tradeoff with each other. If a location was not suitable for any criterion, then it could not be suitable on the final map. (We also explored the Boolean OR (maximum) operation, which was too risk-taking to be of much use.)

WLC, however, allowed us to use the full potential of our factors as continuous surfaces of suitability. Recall that after identifying the factors, they were standardized using fuzzy functions, and then weighted and combined using an averaging technique. The factor weights used expressed the relative importance of each criterion for the overall objective, and they determined how factors were able to trade off with each other. The final map of continuous suitability for residential development (MCEWLC) was the result of an operation that can be said to be exactly halfway between the AND and OR operations. It was neither extremely risk-averse nor extremely risk-taking. In addition, all factors were allowed to fully tradeoff. Any factor could compensate for any other according to its factor weight.

Thus the MCE procedures we used in the previous two exercises lie along a continuum from AND to OR. The Boolean method gives us access to the extremes while the WLC places the operation exactly in the middle. At both extremes of the continuum, tradeoff is not possible, but in the middle there is the potential for full tradeoff. The aggregation method we will use in this exercise, OWA, will give us control over the position of the MCE along both the risk and tradeoff axes (refer to Figure 1 of the previous exercise). That is, it will let us control the level of risk we wish to assume in our MCE, and the degree to which factor weights (tradeoff weights) will influence the final suitability map. OWA offers a wealth of possible solutions for our residential development problem.

Control over risk and tradeoff is made possible through a set of order weights for the different rank-order positions of factors at every location (pixel). The order weights will first modify the degree to which factor weights will have influence in the aggregation procedure, thus they will govern the overall level of tradeoff. After factor weights are applied to the original factors (to some degree dependent upon the overall level of tradeoff used), the results are ranked from low to high suitability for each location. The factor with the lowest suitability score is then given the first Order Weight, the factor with the next lowest suitability score is given the second Order Weight, and so on. This has the effect of weighting factors based on their rank from minimum to maximum value for each location. The relative skew toward either minimum or maximum of the order weights controls the level of risk in the evaluation. Additionally, the degree to which the order weights are evenly distributed across all positions controls the level of overall tradeoff, i.e., the degree to which factor weights have influence.

The user should review the chapter on **Decision Support: Decision Strategy Analysis** in the **IDRISI Guide to GIS and Image Processing** for more information on OWA. Please keep in mind that the OWA technique as implemented in IDRISI is relatively new and experimental. The examples below, like the preceding exercises, are hypothetical.

Average Risk and Full Tradeoff

In our example, we need to specify six order weights because we have six factors that will be rank-ordered for each location after the modified factor weights are applied. If we want to produce a result identical to our WLC example where our level of risk is exactly between AND and OR and our level of tradeoff is full (i.e., factor weights are employed fully), then we would specify the following order weights:

Table 1:

Average Level of Risk - Full Tradeoff

Order Weights:	0.16	0.16	0.16	0.16	0.16	0.16
Rank:	1st	2nd	3rd	4th	5th	6th

In the above example, weight is distributed or dispersed evenly among all factors regardless of their rank-order position from minimum to maximum for any given location. They are skewed toward neither the minimum (AND operation) nor the maximum (OR operation). As in the WLC procedure, our result will be exactly in the middle in terms of risk. In addition, because all rank order positions are given the same weight, no rank-order position will have a greater influence over another in the final result.[48] There will be full tradeoff between factors, allowing the factor weights to be fully employed. To see the result of such a weighting scheme, and to explore a range of other possible solutions for our residential development problem, we will again use the Decision Wizard.

a) Open the Decision Wizard and retrieve the Decision Wizard file called WLC, saved during the WLC procedure in the previous exercise. Click the Next button. Click Yes when prompted about saving the file. Then click Save As and give the filename MCEAVG. By doing this, we will be able to make changes to the decision rule while maintaining the original MCEWLC decision wizard file.

   Click Next several times until you come to the **Ordered Weighted Averaging** (OWA) screen. (It has a figure showing the Decision Strategy space.) Choose the OWA option. Click the Next button to go to the next step.

b) **Specify Order Weights**. A set of order weights appears on the screen. In this case, they are equal for all factors. (Although order weights were not used in the MCEWLC model, equal order weights were automatically stored in the Decision Wizard file.) These order weights will produce a solution with full tradeoff and average risk. Click the spot at the top of the triangle to verify that these weights correspond to the top of the triangular decision space.

c) **Summary of Decision Rule and Output MCE Filename**. Click the Next button. Call the new output image MCEAVG. Check that all the parameters of the new model are correct (for example, click on the OWA weights to see if they are included in the model). Click Next.

d) When MCE has finished processing, the resulting image, MCEAVG, will be displayed. Also display the WLC result, MCEWLC, and arrange the images such that both are visible. These images are identical. As previously discussed, the WLC technique is simply a subset of the OWA technique. Click on the Finish button and close the Wizard.

The results from any OWA operation will be a continuous image of overall suitability, although each may use different levels of tradeoff and risk. These results, like that from WLC, present a problem for site selection as in our example.

48. It is important to remember that the rank-order for a set of factors for a given location may not be the same for another location. Order weights are not applied to an entire factor image, but on a pixel by pixel basis according to the pixel values' rank orders.

Where are the best sites for residential development? Will these sites be large enough for a housing development? The next exercise will address site selection methods. In the remainder of this exercise, we will explore the result of altering the order weights in the MCE-OWA.

Low Risk and No Tradeoff

If we want to produce a low risk result for our residential development problem, one close to AND (minimum) on the risk continuum, then we would give greater order weight to the lower rank-orders (the minimum suitability values). In fact, if we give full weight to the first rank-order (the minimum suitability score across all factors for each pixel), our result will closely resemble the AND operation we used in our Boolean MCE. In addition, such a weighting would result in no tradeoff. The factor weights we developed earlier would influence the ranking process, but the suitability score assigned would not be weighted. The order weights we would use for this AND operation would be the following:

Table 2:

Low Level of Risk - No Tradeoff

Order Weights:	1	0	0	0	0	0
Rank:	1st	2nd	3rd	4th	5th	6th

In this AND operation example, all weight is given to the first ranked position, the factor with the minimum suitability score for a given location. Clearly this set of order weights is skewed toward AND; the factor with the minimum value gets full weighting. In addition, because no rank-order position other than the minimum is given any weight, there can be no tradeoff between factors. The minimum factor alone determines the final outcome.

e) Close all open windows. Open the Decision Wizard and retrieve the Decision Wizard file called MCEAVG, created earlier in this exercise. Click the Next button, then OK when prompted about saving the file. Click Save As and name this Decision Wizard file MCEMIN.

f) **Specify Order Weights**. Click Next several times until you come to the screen where order weights are set. Click the spot in the lower left corner of the figure. This will change the order weights such that they produce the minimum operation, as shown above. Click the Next button. Examine the decision rule information and call the new output image MCEMIN. Click the Next button.

g) Close all windows then use DISPLAY Launcher to access the Pick List. Find the group file MCEMIN in the Pick List and open it by clicking on the plus sign. (This group file was previously created using IDRISI Explorer.) Choose MCEMIN and display it with the Default IDRISI Quantitative palette. Use the Feature Properties query tool to explore the values in the image. (You can drag the Feature Properties box to be near the image so you can more easily see where you are querying and the resulting values.)

1 *What factor appears to have most determined the final result for each location in MCEMIN? What influence did factor weights have in the operation? Why?*

2 *For comparison, display your Boolean result, MCEBOOL (with the qualitative palette), alongside MCEMIN. Clearly these images have areas in common. Why are there areas of suitability that do not correspond to the Boolean result?*

An important difference between the OWA minimum result and the earlier Boolean result is evident in areas that are highly suitable in both images. Unlike in the Boolean result, in the MCEOWA result, areas chosen as suitable retain information about varying degrees of suitability.

h) Now, let's create an image called MCEMAX that represents the maximum operation using the same set of factors and constraints. Open the Decision Wizard and retrieve the Decision Wizard file called MCEMIN, created earlier in this exercise. Click the Next button and OK when prompted to save the file. Click Save As and call this file MCEMAX.

i) **Specify Order Weights**. Click Next several times until you come to the screen where order weights are set. Click the spot in the lower right corner of the figure. This will change the order weights such that they produce the maximum operation.

3 What order weights yield the maximum operation? What level of tradeoff is there in your maximum operation? What level of risk?

j) Click the Next button. Examine the decision rule information and call the new output image MCEMAX.

Close all windows, then display the image MCEMAX from the groupfile called MCEMAX. Use the Feature Properties query to explore the values in the image.

4 Why do the non-constrained areas in MCEMAX have such high suitability scores?

The minimum and maximum results are located at the extreme ends of our risk continuum while they share the same position in terms of tradeoff (none). This is illustrated in Figure 1.

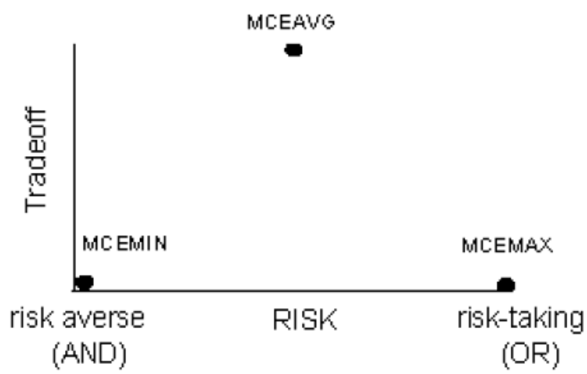


Figure 1

Varying Levels of Risk and Tradeoff

Clearly the OWA technique can produce results that are very similar to the AND, OR, and WLC results. In a way these are all subsets of OWA. However, because we can alter the order weights in terms of their skew and dispersion, we can produce an almost infinite range of possible solutions to our residential development problem, i.e., solutions that fall anywhere along the continuum from AND to OR and that have varying levels of tradeoff.

For example, in our residential development problem, town planners may be interested in a conservative or low-risk solution for identifying suitable areas for development. However, they also know that their estimates for how different factors should trade off with each other are also important and should be considered. The AND operation will not let them consider any tradeoff, and the WLC operation, where they would have full tradeoff, is too liberal in terms of risk. They will then want to develop a set of order weights that would give them some amount of tradeoff but would maintain a level of low risk in the solution.

There are several sets of order weights that could be used to achieve this. For low risk, the weight should be skewed to the minimum end. For some tradeoff, weights should be distributed through all ranks. The following set of order weights was used to create the image MCEMIDAND.

Table 3:

Low Level of Risk - Some Tradeoff

Order Weights:	0.5	0.3	0.125	0.05	0.025	0.0
Rank:	1st	2nd	3rd	4th	5th	6th

Notice that these order weights specify an operation midway between the extreme of AND and the average risk position of WLC. In addition, these order weights set the level of tradeoff to be midway between the no tradeoff situation of the AND operation and the full tradeoff situation of WLC.

k) Display the image MCEMIDAND from the group file called MCEMIDAND. (The remaining MCE output images have already been created for you to save time. However, the Decision Wizard file for each is included in the data set and you may open them with the Wizard if you like.)

l) Display the image MCEMIDOR from the group file called MCEMIDOR. The following set of order weights was used to create MCEMIDOR.

Table 4:

High Level of Risk - Some Tradeoff

Order Weights:	0.0	0.025	0.05	0.125	0.3	0.5
Rank:	1st	2nd	3rd	4th	5th	6th

5 *How do the results from MCEMIDOR differ from MCEMIDAND in terms of tradeoff and risk? Would the MCE-MIDOR result meet the needs of the town planners?*

6 *In a graph similar to the risk-tradeoff graph above, indicate the rough location for both MCEMIDAND and MCE-MIDOR.*

m) Close all open display windows and use DISPLAY Launcher to access the Pick List. Find the group file MCE-OWA in the Pick List and open it by clicking on the plus sign. This file includes all five results from the OWA procedure in order from AND to OR (i.e., MCEMIN, MCEMIDAND, MCEAVG, MCEMIDOR, MCE-MAX). Display any one of these as a member of the group, then use the Feature Properties query tool to explore the values in these images. It may be easier to use the graphic display in the Feature Properties box. To do so, click on the View as Graph button at the bottom of the box.

While it is clear that suitability generally increases from AND to OR for any given location, the character of the increase between any two operations is different for each location. The extremes of AND and OR are clearly dictated by the minimum and maximum factor values, however, the results from the middle three tradeoff operations are determined by an averaging of factors that depends upon the combination of factor values, factor weights, and order weights. In general, in locations where the heavily weighted factors (slopes and roads) have similar suitability scores, the three results with tradeoff will be strikingly similar. In locations where these factors do not have similar suitability scores, the three results with tradeoff will be more influenced by the difference in suitability (toward the minimum, the average, or the maximum).

In the OWA examples explored so far, we have varied our level of risk and tradeoff together. That is, as we moved along the continuum from AND to OR, tradeoff increased from no tradeoff to full tradeoff at WLC and then decreased to no tradeoff again at OR. Our analysis, graphed in terms of tradeoff and risk, moved along the outside edges of a triangle, as shown in Figure 2.

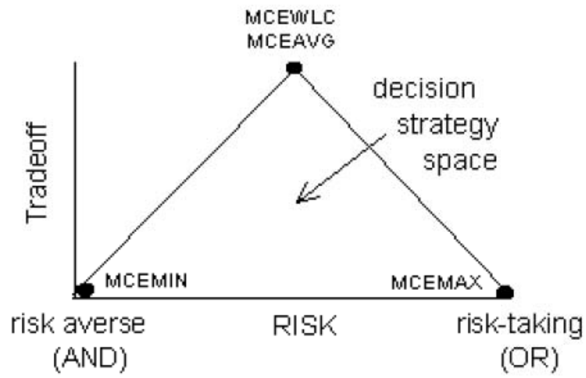


Figure 2

However, had we chosen to vary risk independent of tradeoff we could have positioned our analysis anywhere within the triangle, the *Decision Strategy Space.*

Suppose that the no tradeoff position is desirable, but the no tradeoff positions we have seen, the AND (minimum) and OR (maximum), are not appropriate in terms of risk. A solution with average risk and no tradeoff would have the following order weights.

Table 5:

Average Level of Risk - No Tradeoff

Order Weights:	0.0	0.0	0.5	0.5	0.0	0.0
Rank:	1st	2nd	3rd	4th	5th	6th

(Note that with an even number of factors, setting order weights to absolutely no tradeoff is impossible at the average risk position.)

7 *Where would such an analysis be located in the decision strategy space?*

n) Display the image called MCEARNT (for average risk, no tradeoff). Compare MCEARNT with MCE. (If desired, you can add MCEARNT to the MCEOWA group file by opening the group file in IDRISI Explorer, adding MCEARNT, then saving the file.)

MCEAVG and MCEARNT are clearly quite different from each other even though they have identical levels of risk. With no tradeoff, the average risk solution, MCEARNT, is near the median value instead of the weighted average as in MCEAVG (and MCEWLC). As you can see, MCEARNT breaks significantly from the smooth trend from AND to OR that we explored earlier. Clearly, varying tradeoff independently from risk increases the number of possible outcomes as well as the potential to modify analyses to fit individual situations.

Grouping Factors According to Tradeoff

Our analysis so far has assumed that all factors must trade off according to the same level prescribed by one set of order weights. However, as discussed earlier in this example, our factors are of two distinct types: factors relevant to development cost and factors relevant to environmental concerns. These two sets do not necessarily have the same level of tradeoff. Factors relevant to the cost of development clearly can fully trade off. Where financial cost is the common concern, savings in development cost in one factor can compensate for a high cost in another. Factors relevant to environmentalists, on the other hand, do not easily trade off. Keeping wildlife habitat distant from new development does not compensate for water runoff and contamination concerns.

To cope with this discrepancy, we will treat our factors as two distinct sets with different levels of tradeoff specified by two sets of ordered weights. This will yield two intermediate suitability maps. One is the result of combining all financial factors, and the other is the result of combining both environmental factors. We will then combine these intermediate results using a third MCE operation.

For the first set of factors, those relevant to cost, we will use the WLC procedure to combine them since we want a result that yields full tradeoff and average risk. There are four cost factors to consider: current landuse, distance from town center, distance from roads, and slope. The WLC procedure allows factor weights to fully influence the result, and the cost factors have already been weighted along with the environmental factors such that all six original factor weights summed to 1. However, we will have to create new weights for the four cost factors such that they sum to 1 without the environmental factors. For this example, rather than re-weighting our four cost factors, we will simply rescale the weights previously calculated such that they sum to 1. The original constraints (LANDCON and WATERCON) were also applied.

Table 6:

	Original Weights	Rescaled Weights
LANDFUZZ	0.0620	0.0791
TOWNFUZZ	0.0869	0.1108
ROADFUZZ	0.3182	0.4057
SLOPEFUZZ	0.3171	0.4044

o) Display the COSTFACTORS image. (The Decision Wizard file is in the data directory if you wish to examine the parameters.)

For the second set of factors, those relevant to environmental concerns, we will use an OWA procedure that will yield a low risk result with no trade off (i.e. the order weights will be 1 for the 1st rank and 0 for the 2nd). There are two factors to consider: distance from water bodies and wetlands and distance from already developed areas. Again, we will rescale the original factor weights such that they sum to 1 and apply the original constraints.

Table 7:

	Original Weights	Rescaled Weights
WATERFUZZ	0.1073	0.4972
DEVELOPFUZZ	0.1085	0.5028

p) Display the image ENVFACTORS. (The Decision Wizard file is in the data directory if you wish to examine the parameters.)

Clearly these images are very different from each other. However, note how similar COSTFACTORS is to MCEWLC.

8 *What does the similarity of MCEWLC and COSTFACTORS tell us about our previous average risk analysis? Which factors most influence the results in COSTFACTORS and ENVFACTORS?*

The final step in this procedure is to combine our two intermediate results using a third MCE operation. In this aggregation, COSTFACTORS and ENVFACTORS are treated as factors in a separate aggregation procedure. There is no clear rule as to how to combine these two results. We will assume that our town planners are unwilling to give more weight to either the developers' or the environmentalists' factors; the factor weights will be equal. In addition, they will not allow the two new consolidated factors to trade off with each other, nor do they want anything but the lowest level of risk when combining the two intermediate results.

9 *What set of factor and order weights will give us this result?*

q) Dipslay an image called MCEFINAL.

10 *How does MCEFINAL differ from previous results? How did the grouping of factors in this case affect outcomes?*

Save the image MCEFINAL for use in the following exercise. OWA offers an extraordinarily flexible tool for MCE. Like traditional WLC techniques, it allows us to combine factors with variable factor weights. However, it also allows control over the degree of tradeoff between factors as well as the level of risk one wants to assume. Finally, in cases where sets of factors clearly do not have the same level of tradeoff, OWA allows us to temporarily treat them as separate suitability analyses, and then to recombine them. While still somewhat experimental, OWA as a GIS technique for non-Boolean suitability analysis and decision making is potentially revolutionary.

Answers

1. The factor with the lowest rank for each pixel has the most influence. Factor weights influence the ranking, but because there is no tradeoff, the final suitability score assigned is that of the lowest-ranked factor.

2. There are differences because the factors were standardized differently. Some suitability remains in the fuzzy factors beyond the Boolean cutoff points we used in the Boolean factors.

3.

Table 8:

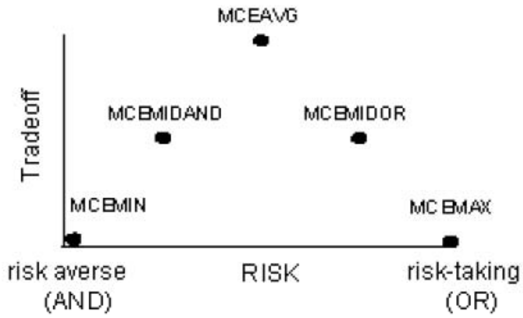
Maximum Operation: High Level of Risk - No Tradeoff

Order Weights:	0	0	0	0	0	1
Rank :	1st	2nd	3rd	4th	5th	6th

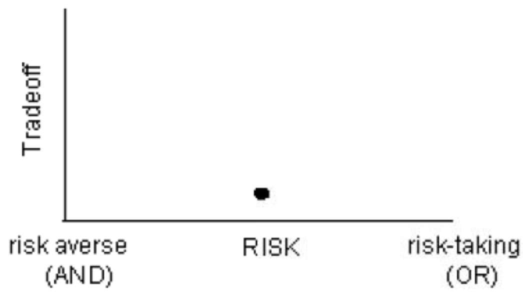
4. The suitability scores are so high because for every pixel, at least one factor has a fairly high score.

5. Both offer the same amount of tradeoff, but MCEMIDAND is moderately risk-averse while MCEMIDOR is moderately risk-taking. The MCEMIDOR result is too risky for the town planners.

6.



7.



8. The similarity of MCEWLC and COSTFACTORS indicates that in MCEWLC, the developers' concerns formed the bulk of the decision about suitability. Distance from roads and slopes most influenced the COSTFACTORS image while the highest scores for the ENVFACTORS image appear to be near currently-developed areas.

9. The factor weights are 0.5 and 0.5.

Table 9:

Low Risk - No Tradeoff

Order Weights :	1	0
Rank :	1st	2nd

10. The environmental concerns clearly have much more influence on this result than on any other result we produced.

Exercise 2-10
MCE: Site Selection Using Boolean and Continuous Results

This exercise uses the results from the previous three exercises to address the problem of site selection. While a variety of standardization and aggregation techniques are important to explore for any multi-criteria problem, they result in images that show the suitability of locations in the entire study area. However, multi-criteria problems, as in the previous exercises, often concern eventual site selection for some development, land allocation, or landuse change. There are many techniques for site selection using images of suitability. This exercise explores some of those techniques in the context of finding the most suitable sites for residential development.

Site Selection using the Boolean Result

Using the result of the Boolean analysis to select sites for residential development is rather straightforward because all areas have been divided into suitable or unsuitable so there are no degrees of suitability to consider. Consequently, there are no "second best" areas for residential development, nor are there judgments to be made about the best location within areas judged to be suitable. However, there remains the problem of size and spatial contiguity of suitable areas.

The areas chosen as suitable are fragmented throughout the study area and most are probably too small for a residential development project. Many are only a few hundred square meters in size. We can address this problem by adding a post-aggregation constraint: areas suitable for development must be 20 hectares or larger.

a) Display MCEBOOL, the result from Exercise 2-7. Using a combination of the modules GROUP, AREA, RECLASS, and OVERLAY in a sequence identical to that used in the latter part of Exercise 2-3, contiguous areas greater than or equal to 20 hectares were found. The result is the image BOOLSIZE20. Display this image.

This approach results in several potential sites from which to choose. However, due to their Boolean nature, their relative suitability cannot be judged and it would be difficult to make a final choice between one or another site. A non-Boolean approach will give us more information to compare potential sites with each other.

Site Selection using Continuous Suitability Images

The WLC and OWA approaches result in continuous suitability images that make selecting specific sites for residential development, or any other allocation, problematic. In the Boolean approach, site suitability was clearly defined (though rather arbitrarily) and the only problem for site selection was one of contiguity. This was addressed by adding the post-aggregation constraint that suitable sites must be at least 20 hectares in size. With a continuous result, there is first the problem of deciding what locations should be chosen from the set of all locations, each of which has some degree of suitability. Only after this is established can the problem of contiguity be addressed as in the Boolean result.

There are several methods for site selection using a continuous image of suitability. Here we will explore two basic approaches. In the first approach, some level of suitability is specified as a threshold for considering a location finally suitable or not. For example, all locations with a suitability score of at least 200 will be selected as appropriate for some allocation while those with a score below 200 will not be selected. This hard decision results in a Boolean map indicating all possible sites.

In the second approach, it is not the degree of suitability but the total quantity of land for selection (or allocation to a new use) that determines a threshold. In this case, all locations (i.e., pixels) are ranked by their degree of suitability. After ranking, pixels are selected/allocated based on their suitability until the quantity of land needed is achieved. For example, 1000 hectares of land might need to be selected/allocated for residential development. Using this approach, all locations are ranked and then the most suitable 1000 hectares are selected. The result is again a Boolean map indicating selected sites.

Both types of thresholds (by suitability score or by total area) can be thought of as additional post-aggregation constraints. They constrain the final result to particular locations. However, it should be noted that they do not address the problem of contiguity and site size. It is only after thresholding (when a Boolean image is produced) that results can be assessed in terms of contiguity and size using methods similar to those described above.

In addition to these essentially Boolean solutions to site selection using a continuous suitability image, non-Boolean solutions to site selection are perhaps possible using anisotropic surface calculations. However, these methods are not well developed at this time and will not be addressed in this exercise.

Suitability Thresholds

A threshold of suitability for the final site selection may be arbitrary or it may be grounded in the suitability scores determined for each of the factors. For example, during the standardization of factors, a score of 200 or above might have been thought to be, on average, acceptable while below 200 was questionable in terms of suitability. If this was the logic used in standardization, then it should also be applicable to the final suitability map. Let's assume this was the case and use a score of 200 as our suitability threshold for site selection. This is a post-aggregation constraint. We will use the result from Exercise 2-8 (MCEWLC) but you could follow these procedures using any of the continuous suitability results from either Exercise 2-8 or 2-9.

b) Run RECLASS from the GIS Analysis/Database Query menu and specify MCEWLC as the input image and SUIT200 as the output image. Then enter the following values into the reclassification parameters area of the dialog box:

New value	Old values from	To those just less than
0	0	200
1	200	999

The result is a Boolean image of all possible sites for residential development. However, it is a highly fragmented image with just a few contiguous areas that are substantial. Let's assume that another post-aggregation constraint must be applied here as well, that a suitable site be 20 hectares or greater.

c) Use GROUP (with diagonals) and AREA to determine if there are any areas 20 hectares or larger in size. (Remember to remove the unsuitable groups.) Call the resulting image SUIT200SIZE20 (for suitability threshold 200, site size 20 hectares).

   1 *What is the size of the largest potential site for residential development?*

d) Clearly, given the post-aggregation constraints of both a suitability threshold of 200 and a site size of 20 hectares or greater, there are no suitable sites for residential development. Assuming town planners want to continue with site selection, there are a number of ways to change the WLC result. Town planners might use different factors or combinations of factors, they might alter the original methods/functions used for standardization of factors, they might weight factors differently, or they might simply relax either or both of the post-aggregation constraints (the suitability threshold or the minimum area for an acceptable site).

In general, non-Boolean MCE is an iterative process and you are encouraged to explore all of the options listed above to change the WLC result.

Using Macros for Iterative Analysis

In the site selection problem of this exercise, we need to run the same set of operations that we performed above over and over, each time changing one parameter, to iteratively arrive at an acceptable final solution. You saw in several of the earlier exercises of this section of the Tutorial how Macro Modeler can be used to achieve easy automation of such analyses. In this exercise, you will be exposed to IDRISI's non-graphic macro scripting language.

The macro we will use has been provided and is called SITESELECT.

e) Use Edit, from the Data Entry menu, to examine a macro file (.iml) named SITESELECT. Don't make any changes to the file yet.

The macro scripting language uses a particular syntax for each module to specify the parameters for that module. For more information on these types of macros, see the chapter **IDRISI Modeling Tools** in the **IDRISI Guide to GIS and Image Processing**. The particular command line syntax for each module is specified in each module description in the on-line Help System.

The macro uses a variety of IDRISI modules to produce two maps of suitable sites.[48] One map shows each site with a unique identifier and the other shows sites using the original continuous suitability scores. The former is automatically named SITEID by the macro. It is used as the feature definition file to extract statistics for the sites. The other map is named by the user each time the macro is run (see below). The macro also reports statistics about each site selected. These include the average suitability score, range of scores, standard deviation of scores, and area in hectares for each site.

Note that some of the command lines contain symbols such as %1. These are placeholders for user-defined inputs to the macro. The user types the proper values for these into the macro parameters input box on the Run Macro dialog box. The first parameter entered is substituted into the macro wherever the symbol %1 is placed, the second is substituted for the %2 symbol, and so on. Using a macro in this way allows you to easily and quickly change certain parameters without editing and re-saving the macro file. The SITESELECT macro has four placeholders, %1 through %4. These represent the following parameters:

%1 the name of the continuous suitability map to be analyzed

%2 a suitability threshold to use

%3 the minimum site size (in hectares)

%4 the name of the output image with the suitable sites masked and each site containing its continuous values from the original suitability map

Now that we understand the macro, we will use it to iteratively find a solution to our site selection problem. (Note that in Macro Modeler, you would change these parameters by linking different input files, renaming output files and editing the .rcl files used by RECLASS)

f) Close Edit. If prompted to save any changes, click No.

Earlier, a suitability level of 200 and a site size of 20 hectares resulted in no selected sites from MCEWLC. Therefore, we will reduce the site size threshold to 10 hectares to see if any sites result.

g) Choose the Run Macro command from the File menu. Enter SITESELECT as the macro file to run. In the Macro Parameters input box, type in the following four macro parameters as shown, with a space between each:

48. Any lines that begin with "rem" are remarks. These are for documentation purposes and are ignored by the macro processor.

MCEWLC 200 10 SUIT200SIZE10

These parameters ask the macro to analyze the image MCEWLC, isolate all locations with a suitability score of 200 or greater, from those locations find all contiguous areas that are at least 10 hectares in size, and output an image called SUIT200SIZE10 (for suitability of 200 or greater and sites of 10 hectares or greater). Click OK and wait while the macro runs several IDRISI modules to yield the result.

The macro will output two images and two tables.

It will first display the sites selected using unique identifiers (the image will be called SITEID).

It will then display a table that results from running EXTRACT using the image SITEID as the feature definition image and the original suitability image, MCEWLC, as the image to be processed. Information about each site, important to choosing amongst them, is displayed in tabular format.

The macro will then display a second table listing the identifier of each site along with its area in hectares.

Finally, it will display the sites selected using the original suitability scores. This final image will be called SUIT200SIZE10.

The images output from the SITESELECT macro show all locations that are suitable using the post-aggregation constraints of a particular suitability threshold and minimum site size. The macro can be run repeatedly with different thresholds.

2 *How many sites are selected now that the minimum area constraint has been lowered to 10 hectares? How might you select one site over another?*

h) Visually compare SUIT200SIZE10 to the final result from the Boolean analysis (BOOLSIZE20).

3 *What might account for the sites selected in the WLC approach that were not selected in the Boolean approach?*

Rather than reducing the minimum area for site selection, planners might choose to change the suitability threshold level. They might lower it in search of the most suitable 20 hectare sites.

i) Run the SITESELECT macro a second time using the following parameters that lower the suitability threshold to 175:

MCEWLC 175 20 SUIT175SIZE20

These parameters ask the macro to again analyze the image MCEWLC, isolate all locations with a suitability score of 175 or greater, find sites of 20 hectares or greater, and output the image SUIT175SIZE20 (i.e., suitability 175 and hectares 20).

4 *How many sites are selected? How would you explain the differences between SUIT200SIZE10 and SUIT175SIZE20?*

j) Finally, lower the suitability threshold to 150, retain the 20 hectare site size, and run the macro again. Call the resulting image SUIT150SIZE20.

The difference in the size and quantity of sites selected from a suitability level of 175 to 150 is striking. In the case where the threshold is set at 150, the number of sites may be too great to reasonably select amongst them. Also, note that as the size of sites grow, appreciable differences within those large sites in terms of suitability can be seen. (This can be verified by checking the standard deviations of the sites.)

k) To help explain why there is such a change in the number and size of sites, run HISTO from GIS Analysis/Statistics with MCEWLC as the input image and a display minimum of 1.

5 *What helps to explain the increase in the number and size of selected sites between suitability levels 175 and 150?*

Selecting a variety of suitability thresholds, different minimum site sizes, and exploring the results is relatively easy with the SITESELECT macro. However, justifying the choices of threshold and site size is dependent solely on the human element of GIS. It can only be done by participants in the decision making process. There is no automated way to decide the level of suitability nor the minimum site size needed to select final sites.

Specifying a Total Area Threshold

The second basic approach to selecting locations from the continuous suitability map (e.g., MCEWLC) is by ranking all locations (pixels) in terms of suitability and then selecting a fixed quantity of top-ranked locations (e.g., equivalent to 1000 hectares). The result would be a Boolean map where an exact amount of land is selected or allocated for new use. The selected land can then be analyzed in terms of contiguity as in the previous examples.

While this may be easily accomplished with the modules RANK and RECLASS, the Decision Wizard includes a facility to easily create such area threshold images. (In fact, it uses RANK and RECLASS.)

l) Open the Decision Wizard. Click Next, then choose to open the existing Decision Wizard file called WLC. Click Next several times until you arrive at the last screen of the Wizard, which has a checkbox labeled **Select Best Area for This Objective**. Click the check box.

Information about the input file, MCEWLC, is shown including the total number of cells in the image and the resolution of the image (as read from the metadata file). A drop-down box of areal measurement units is provided from which you may select the units in which you would like to specify the area threshold. Choose Hectares. Note that the total number of hectares in the image is now shown.

m) Click in the Units input box and choose Hectares from the drop-down list. Then enter 1000 as the areal requirement. Change the output image name to be BEST1000. Click Finish. The output Boolean result will display after RANK and RECLASS have run.

n) When prompted whether to close the Wizard, click No. Change the area requirement to 2000 hectares, change the output image name to BEST2000 and click Finish again. This time click Yes to close the Wizard.

6 *What problem might be associated with selecting sites for residential development from the most suitable 2000 hectares in MCEWLC?*

The results of this total area threshold approach can be used to allocate specific amounts of land for some new development. However, it cannot guarantee the contiguity of the locations specified since the selection is on a pixel by pixel basis from the entire study area. These Boolean results must be submitted to the same grouping and reclassification steps described in the previous section to address issues of contiguity and site size.

o) Open the Decision Wizard again and step through the decision file called MCEFINAL, which was created in Exercise 2-9. When you reach the end, request to find the best 2000 hectares from this model. Call the result BEST2000FINAL. Note the very different result. The MCEFINAL produces a much less fragmented pattern.

7 *What might explain the very different patterns of the most suitable 2000 hectares from each suitability map?*

Using a total area threshold works well for selecting the best locations for phenomena that can be distributed throughout the study area or for datasets that result in high levels of autocorrelation (i.e., suitability scores tend to be similar for neighboring pixels).

Our exploration of MCE techniques has thus far concentrated on a single objective. The next exercise introduces tools that may be used when multiple objectives must be accommodated.

Answers

1. The largest site is only 17.7 hectares.

2. There are three sites, with areas 17.7, 13.2 and 10.8 hectares. There may be several ways to choose one over another. You might choose one site over another based on the highest average suitability, for example.

3. The WLC result required only 10 contiguous hectares while the Boolean required 20. Also, it is possible that one or more of the factors was not suitable in the Boolean approach, yet had some level of suitability in the WLC. If that factor had a low score, but also had a low factor weight (e.g., WATERFUZZ), then the overall suitability score in the WLC image could still be quite high.

4. There are three sites. Two overlap with and are larger than sites in SUIT200SIZE10. Dropping the suitability to 175 allowed more pixels to be included in the sites. The upper right site of SUIT200SIZE10 does not appear in SUIT175SIZE20. Not enough of the surrounding pixels had suitability greater than 175, so the 20 hectare limit was not reached. There is a new site in the lower left portion of the study area. Here, there were not enough contiguous pixels to form even a 10 hectare site at suitability 200, but when the suitability was lowered to 175 enough pixels were found to meet the 20 hectare size limit.

5. The histogram of MCEWLC shows a peak around suitability score 135. When the threshold is dropped from 175 to 150 quite a large number of pixels become suitable.

6. There are many areas from which to choose. Many of the areas are very small.

7. The MCEFINAL image gives more importance to the environmental factors, distance from water and distance from developed areas. Distance factors are by nature highly autocorrelated. Therefore the resulting suitability image should have a higher degree of autocorrelation than MCEWLC. (The slope gradient factor was quite important in its development and is much less autocorrelated.) When suitability images are highly autocorrelated, high suitability scores tend to be next to high suitability scores. This may make it easier to find contiguous areas of similar suitability.

Exercise 2-11
MCE: Multiple Objectives

In the previous four exercises, we have explored multi-criteria evaluation in terms of a single objective—suitability for residential development. However, it is often the case that we need to make site selection or land allocation decisions that satisfy multiple objectives, each expressed in its own suitability map. These objectives may be complementary in terms of landuse (e.g., open space preservation and market farming) or they may be conflicting (e.g., open space preservation and retail space development).

Complementary objective problems are easily addressed with MCE analyses. We simply treat each objective's suitability map as a factor in an additional MCE aggregation step. The case of conflicting or competing objectives, however, requires some mechanism for choosing between objectives when a location is found highly suitable for more than one. The Multi-Objective Land Allocation (MOLA) module in IDRISI employs a decision heuristic for this purpose. It is designed to allocate locations based upon total area thresholds as in the last part of the previous exercise. However, the module simultaneously resolves areas where multiple objectives conflict. It does so in a way to provide a best overall solution for all objectives. For details about the operation of MOLA, review the chapter **Decision Support: Decision Strategy Analysis** found in the **IDRISI Guide to GIS and Image Processing**.

To illustrate the multi-objective problem, we will use MOLA to allocate land (up to specified area thresholds) for two competing objectives, residential development and industrial development in Westborough. As noted above, total area thresholding can be thought of as a post-aggregation constraint. In this example, there is one constraint for each objective. Town planners want to identify the best 1600 hectares for residential development as well as the best 600 hectares for industrial expansion. We will use the final suitability map from Exercise 2-9, MCEFINAL, for the residential development suitability map. A Decision Wizard file including the parameters for MCEFINAL (the residential suitability model) and those for the second objective, industrial suitability, is provided.

a) Open the Decision Wizard. Click Next and choose the Decision Wizard file MOLA. Step through all the pages of the file. You are already familiar with the parameters used for the residential objective, but take some time to examine those specified for the industrial objective. When you reach the end of the residential objective section, choose to select the best 1600 hectares and call the result BEST1600RESID. When you reach the end of the Industrial objective section, choose to select the best 600 hectares and call the results BEST600INDUST.

b) Before we continue with the MOLA process, we will first determine where conflicts in allocation would occur if we treated each of these objectives separately. Leave the Wizard as it is and go to the GIS Analysis / Database Query menu and choose the module CROSSTAB. Enter BEST1600RESID as the first image, BEST600INDUST as the second image, and choose to create a crossclassification image called CONFLICT.

The categories of CONFLICT include areas allocated to neither objective (1), areas allocated to residential objective, but not the industrial objective (2), and areas allocated to both the residential and industrial objectives (3). It is this latter class that is in conflict. (There are no areas that were selected among the best 600 hectares for industrial development that were not also selected among the best 1600 hectares for residential development.)

The image CONFLICT illustrates the nature of the multi-objective problem with conflicting and competing objectives. Since treating each objective separately produces conflicts, neither objective has been allocated its full target area. We could prioritize one solution over the other. For example, we could use the BEST1600RESID image as a constraint in choosing areas for industry. In doing so, we would assign all the areas of conflict to residential development, then choose more (and less suitable) areas for industry to make up the difference. Such a solution is often not desirable. A compromise solution that achieves a solution that is best for the overall situation and doesn't grossly favor any objective may be more appropriate.

The MOLA procedure is designed to resolve such allocation conflicts in a way that provides a compromise solution—a best overall solution for all objectives.

c) Return to the Wizard. You should be at the Multi-Objective Decision Making screen.

Quite often, data cells will have the same level of suitability for a given objective. In these cases we have the choice of breaking ties either by establishing a rank-order randomly, or by looking to the values of the cells in question on another image.[48] In this case, the latter approach is used. The other objective's suitability map is specified as the basis for resolving ties. Thus, we can resolve ties in suitability for residential development by giving higher rank to cells that are less suitable for industrial development. In effect, we are saying that if two pixels are equally suitable for residential development, take the one that is less suitable for industrial development first. This will leave the other, which is better for industrial development, to be chosen for industrial development.

d) Click Next. Like factors in MCE, objectives in MOLA may be weighted, with the objective with the greater weight being favored in the allocation process. In this case, we will use equal weights for the two objectives. Click Next. Note the area requirements specified for each objective and click Next again. Give the final multi-objective land allocation output image the name MOLAFINAL and click Next again.

The MOLA procedure will run iteratively and when finished will display a log of its iterations and the final image.

1 How many iterations did MOLA take to achieve a solution?

e) The MOLA log indicates the number of cells assigned to each objective. However, since we specified the area requirements in hectares, we will check the result by running the module AREA. Choose AREA from the GIS Analysis / Database Query menu. Give MOLAFINAL as the input image, choose tabular output, and units in hectares.

2 How close is the actual solution to the requested area values?

The solution presented in MOLAFINAL is only one of any number of possible solutions for this allocation problem. You may wish to repeat the process using other suitability maps created earlier for residential development or new industrial suitability maps you create yourself using your own factors, weights, and aggregation processes. You may also wish to identify other objectives and develop suitability maps for these. The MOLA routine (and the Decision Wizard) may be used with up to 20 objectives.

Answers

1. The number of iterations (passes) is shown in the text module results box that is displayed after MOLA finishes.

2. The numbers are exact. However, this might not always be the case. Only full cells may be allocated so in the case when the requested area is not equal to an integer number of cells, there will be some small discrepencies in the requested and actual values.

48. The RANK module orders tied pixels beginning with the upper-left most and proceeding left to right, top to bottom. When a secondary sort image is used, any pixels that are tied on both images are arbitrarily ranked in the same manner.

Exercise 2-12
MCE: Conflict Resolution of Competing Objectives

The Kathmandu Valley Case Study

In the previous five exercises on decision support, we explored the tools available in IDRISI for land suitability mapping and land allocation. This exercise will further explore these concepts using a new case study and dataset. We will also circumvent the use of the Decision Wizard so that we may explore individual decision support modules more fully, specifically FUZZY, WEIGHT, MCE, RANK, and MOLA. This exercise assumes the user has familiarity of the concepts and language introduced in the Decision Support chapter of the IDRISI Guide to GIS and Image Processing.

In this exercise, we will consider the case of the expansion of the carpet industry in Nepal and its urbanizing effects on areas traditionally devoted to valley agriculture. After the flight of the Tibetans into Nepal in 1949, efforts were undertaken, largely by the Swiss, to promote traditional carpet-producing technologies as a means of generating local income and export revenues. Today the industry employs over 300,000 workers in approximately 5000 registered factories. Most of these are sited within the Kathmandu Valley. The carpets produced are sold locally as well as in bulk to European suppliers.

In recent years, considerable concern has been expressed about the expansion of the carpet industry. While it is recognized that the production of carpets represents a major economic resource, the Kathmandu Valley is an area that has traditionally been of major importance as an agricultural region. The Kathmandu Valley is a major rice growing region during the monsoon months, with significant winter crops of wheat and mustard (for the production of cooking oil). The region also provides a significant amount of the vegetables for the Kathmandu urban area. In addition, there is concern that urbanization will force the loss of a very traditional lifestyle in the cultural heritage of Nepal.

In an attempt to limit the degree of urban expansion within the Kathmandu area, the Planning Commission of Nepal has stopped granting permission for the development of new carpet factories within the ring road of Nepal, promoting instead the area outside the Kathmandu Valley for such developments. However, there still remains significant growth within the valley.

a) Make sure your working folder is set to MCE in the IDRISI Tutorial folder. Then, to gain an initial sense of the area under consideration, use DISPLAY Launcher to examine the image named KCOMP. This is a false-color composite image using Landsat bands 3, 4 and 5. (Note that the raw Kathmandu Landsat bands used to create the composite are also available in the Introductory GIS folder for exploration, but they will not be used in this case study. These are named KLANDSATB1 through KLANDSATB7)

   The Kathmandu urban area is clearly evident in this image as the large purplish area to the west. The smaller urban region of Bakhtipur can be seen to the east. Agricultural areas show up either as light green (fallow or recently planted) or greenish (young crops). The deep green areas are forested.

The focus of this exercise is the development of a planning map for the Kathmandu Valley, setting aside 1500 hectares outside the Kathmandu ring road in which further development by the carpet industry will be permitted and 6000 hectares in which agriculture will be specially protected. The land set aside for specific protection of agriculture needs to be the best land for cultivation within the valley, while those zoned for further development of the carpet industry should be well-suited for that activity. Remaining areas, after the land is set aside, will be allowed to develop in whatever manner arises.

The development of a planning zone map is a multi-objective/multi-criteria decision problem. In this case, we have two objectives: the need to protect land that is best for agriculture and the need to find other land that is best suited for the carpet industry. Since land can only be allocated to one of these uses at any one time, the objectives are viewed as conflicting -- i.e., they may potentially compete for the same land. Furthermore, each of these objectives require a number of criteria. For example, suitability for agriculture can be seen to relate to such factors as soil quality, slope, distance to water, and so on. In this exercise, a solution to the multi-objective/multi-criteria problem is presented as it was developed with a group of Nepalese government officials as part of an advanced seminar in GIS.[48] While the scenario was developed purely for the purpose of demonstrating decision support techniques and the result does not represent an actual policy decision, it is one that incorporates substantial field work and well-established perspectives.

Each of the two objectives is dealt with as a separate multi-criteria evaluation problem and two separate suitability maps are created. They are then compared to arrive at a single solution that balances the needs of the two competing objectives.

The data available for the development of this solution are as follows:

i. Landuse map derived from Landsat imagery named KVLANDU

ii. Digital elevation model (DEM) named KVDEM

iii. 50 meter contour vector file named DEMCONTOURS

iv. Vector file of roads named KVROADS

v. Vector file of the ring road area named KVRING

vi. Vector file of rivers named KVRIVERS

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48. The seminar was hosted by UNITAR at the International Center for Integrated Mountain Development (ICIMOD) in Nepal, September 28-October 2, 1992.

vii.	Land capability map named KVLANDC

The Landsat TM imagery dates from October 12, 1988. The DEM is derived from the USGS Seamless Data Distribution System at http://seamless.usgs.gov/. All other maps were digitized by the United Nations Environment Program Global Resources Information Database (UNEP/GRID). The roads data are quite generalized and were digitized from a 1:125,000 scale map. The river data are somewhat less generalized and also derived from a 1:125,000 map. The land capability map KVLANDC was digitized from a 1:50,000 scale map with the following legend categories:

IIBh2st Class II soils (slopes 1-5 degrees / deep and well drained). Warm temperate (B = 15-20 degrees) humid (h) climate. Moderately suitable for irrigation (2).

IIIBh Class III soils (slopes 5-30 degrees) / 50-100cm deep and well drained. Warm temperate and humid climate.

IIICp Class III soils and cool temperate (C = 10-15 degrees) perhumid climate.

IVBh Class IV (slope >30 degrees and thus too steep to be cultivated) soils and a warm temperate humid climate.

IBh1 Class I soils (slopes <1 degree and deep) / warm temperate humid climate / suitable for irrigation for diversified crops.

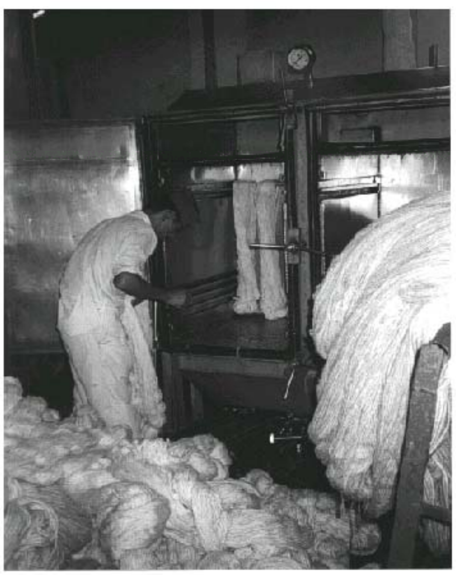
IBh1R Class I soils / warm temperate humid climate / suitable for irrigation for wetland rice.

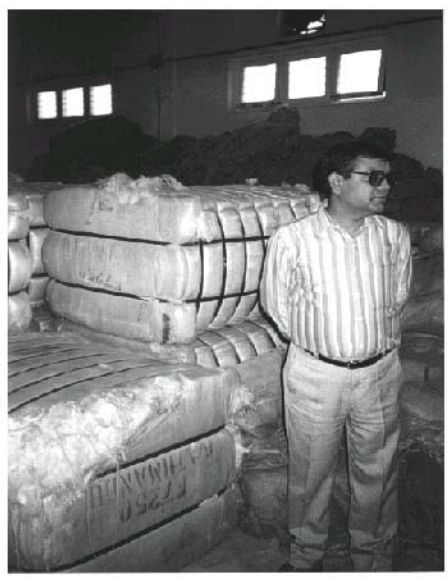
The Multi-Criteria Evaluation for the Carpet Industry

Through discussions, the group of Nepalese officials evaluating this problem decided that the major factors affecting the suitability of land for the carpet industry were as follows:

Proximity to Water

Substantial amounts of water are used in the carpet washing process (see figure next page). In addition, water is also

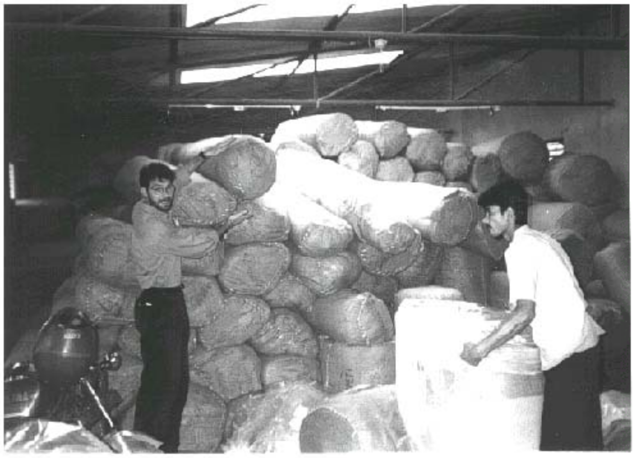




needed in the dying of wool. As a result, close proximity to water is often an important consideration.

Proximity to Roads

The wool used in Nepalese carpets is largely imported from Tibet and New Zealand (see figure below). Access to transportation is thus an important consideration. In addition, the end product is large and heavy, and is often shipped in large lots (see figure above).



Proximity to Power

Electricity is needed for general lighting and for powering the dying equipment (see figure next page). Although not as critical an element as water, proximity to power is a consideration in the siting of a carpet factory.

Proximity to Market

Kathmandu plays an important role in the commercial sale of carpets. With Nepal's growing tourist trade, a sizable market exists within the city itself. Perhaps more importantly, however, commercial transactions often take place within the city and most exports are shipped from the Kathmandu airport.

Slope Gradient

Slope gradient is a relatively minor factor. However, as with most industries, lands of shallow gradient are preferred since they are cheaper to construct and permit larger floor areas. In addition, shallow gradients are less susceptible to soil loss during construction.

In addition to these factors, the decision group also identified several significant constraints to be considered in the zoning of lands for the carpet industry:

Slope Constraint

The group thought that any lands with slope gradients in excess of 100% (45 degrees) should be excluded from consideration.

Ring Road Constraint

Current government policy denies permission for the development of new factories within the ring road that circles Kathmandu.

Landuse Constraint

The problem, as it is presented, is about the future disposition of agricultural land. As a result, only these areas are open for consideration in the allocation of lands to meet the two objectives presented.

The process of developing a suitability map for the carpet industry falls into three stages. First, maps for each of the factors and constraints need to be developed. Second, a set of weights needs to be developed that can dictate the relative influence of each of the factors in the production of the suitability map. Finally, the constraints and factors, along with their associated weights, need to be combined in order to produce the suitability map.

Creating the Criterion Maps

Criteria can be of two types: factors and constraints. Factors are continuous in character and serve to enhance or diminish the suitability of the land for a particular application depending upon the magnitude of the variable in question. Constraints, on the other hand, are Boolean in character. They serve to exclude certain areas from consideration. The development of the carpet industry suitability map involves both kinds of criteria.

Creating the Constraint Maps

For the constraints, all that is required is the development of a Boolean image -- an image containing only zeros and ones -- zeros where development is excluded and ones where it is permitted. In this case, three constraints are involved: slope, the ring road and landuse.

b) Display KVDEM with the default Quantitative palette. To get a better perspective of the relief, use "Add Layer" from Composer to display the vector file DEMCONTOURS. Choose the White Outline symbol file. These are 50 meter contours created from the DEM.

Next run SURFACE on the elevation model KVDEM to create a slope map named KVSLOPES. Specify to calculate the output in slope gradients as percents. Display the result with the Quantitative palette.

Now create the slope constraint map by running RECLASS on the image KVSLOPES to create a new image named SLOPECON. Use the default user-defined classification option to assign a new value of 1 to all values ranging from 0 to just less than 100 and 0 to those from 100 to 999. Then examine SLOPECON with the Qualitative palette. Notice that very few areas exceed the threshold of 100% gradient.

c) Now that the slope constraint map has been created, we need to create the ring road constraint map. We will use the vector ring road area data for this.

After displaying the vector file KVRING, run the module RASTERVECTOR and select to rasterize a vector polygon file. Select KVRING as the input file and give it the output name, TMPCON, for the raster file to create. When you hit OK, the module INITIAL will be called because the corresponding raster file does not yet exist. Using INITIAL, specify the image to copy parameters from as KVDEM and the output data type as byte. Then hit OK.

What we need is the inverse of this map so as to exclude the area inside the ring road. As in the step above, run RECLASS on TMPCON to assign a new value of 1 to all values ranging from 0 to 1 and 0 to those from 1 to 2. Name the output RINGCON.

d) The final constraint map is one related to land use. Only agriculture is open for consideration in the allocation of lands for either objective. Display KVLANDU with the legend and the KVLANDU user-defined palette. Of the twelve land use categories, the Katus, Forest/Shadow, Chilaune and Salla/Bamboo categories are all forest types; two categories are urban and the remaining six categories are agricultural types.

Perhaps the easiest way to create the constraint map here is to use the combination of EDIT and ASSIGN to assign new values to the land use categories. Use EDIT to create an integer attribute values file name TMPLAND as follows:

```
1    1
```

5	1
6	1
7	1
9	1
10	1

Then run ASSIGN and use KVLANDU as the feature definition image, TMPLAND as the attribute values file, and LANDCON as the output file. Note that ASSIGN will assign a zero to any category not mentioned in the values file. Thus the forest and urban categories will receive a zero by default. When ASSIGN has finished, display LANDCON with the Qualitative palette.

This completes our development of the constraint maps for the carpet suitability mapping project.

Creating the Factor Maps

The development of factor maps usually involves two and at times, three, distinct steps. In the first step, the basic factor map will be developed. In the second step, the values in the map will be standardized to a specific range. In the third step, if necessary, values will be inverted to assure that high values on the map correspond to areas more suitable to the objective under consideration. In this case study, all maps will be standardized to a byte range, positive integers from 0 to 255, since the particular procedures we will use all require byte data sets. This range thus provides maximum precision within this limitation.[49]

e) The first factor is that of proximity to water. As we did earlier with the roads, we will first need to create a raster version of the river data. First display the vector file named KVRIVERS. Notice how this is quite a large file covering the entire Bagmati Zone (one of the main provinces of Nepal). The roads data also cover this region. As we did before, we will run RASTERVECTOR, but this time we will rasterize a line file. Input KVRIVERS as the vector line file and call the output KVRIVERS as well. When you hit OK, the module INITIAL will be called since the raster file named in the output does not yet exist. Specify the image to copy parameters from as KVDEM then hit OK. Display the result and note that only the portion of the vector file matching the extent of the initial file was rasterized.

Now run DISTANCE to calculate the distance of every cell from the nearest river. Specify KVRIVERS as the input feature image and TMPDIST as the output image. View the result.

1 What are the minimum and maximum distances of data cells to the nearest river? How did you determine this?

Now run the module FUZZY to standardize the distance values. Use TMPDIST as the input image and WATERFAC as the output. Specify linear as the membership function type, the output data format as byte, and the membership function shape as monotonically decreasing (we want to give more importance to being near a water source than away). Specify the control points for c and d as 0 and 2250, respectively. Hit OK and display the result.

This is the final factor map. Display it with the Quantitative palette and confirm that the higher values are those nearest the rivers (you can use "Add Layer" to overlay the vector rivers to check).The distance image has thus been converted to a standard range of values (to be known as criterion scores) based on the minimum and max-

49. There is nothing inherently special about this range. The procedures in IDRISI were developed to use the byte range because the byte maximizes data throughput in disk intensive operations, and because it was felt that the precision available (256 levels) was more than adequate for problems of this nature.

imum values in the image. Values are thus standardized to a range determined by the extreme values that exist within the study area. Most of the factors will be standardized in this fashion.

f) Now create the proximity to roads factor map. Since the raster version of the roads data has already been created, the procedure will be quick. Run DISTANCE on KVROADS to create a distance image named TMPDIST (yes, this is the same name we used in the previous step -- since the distance image was only a temporary image in the process of creating the proximity image, it may be overwritten). Then run FUZZY on TMPDIST to create ROADFAC. Specify linear as the membership function type, the output data format as byte, and the membership function shape as monotonically decreasing. Specify the control points for c and d as 0 and 2660, respectively. Hit OK and display the result. Confirm that it has criterion scores that are high (e.g., 255) indicating high suitability near the roads and low (e.g., 0) indicting low suitability at the most distant extremes.

g) Now create the proximity to power factor map. We do not have any data on electrical power. However, it is reasonable to assume that power lines tend to be associated with paved (Bitumen) roads. Thus use RECLASS on KVROADS to create TMPPOWER. With the user-defined classification option, assign a value of 0 to all values ranging from 2 to 999. Then display the image to confirm that you have a Boolean map that includes only the class 1 (Bitumen) roads from KVROADS. Use the same procedures as in the above two steps to create a scaled proximity factor map based on TMPPOWER. Call the result POWERFAC.

h) To create the proximity to market map, we will first need to specify the location of the market. There are several possible candidates: the center of Kathmandu, the airport, the center of Patan, etc. For purposes of illustration, the junction of the roads at column 163 and row 201 will be used. First use INITIAL to create a byte binary image with an initial value of 0 based on the spatial parameters of KVLANDU. Call this new image KVMARK. Then use UPDATE to change the cell at row 201 / column 163 to have a value of 1. Indicate 201 for the first and last row and 163 for the first and last column. Display this image with the Qualitative palette to confirm that this was successfully done.

i) In this case, we will use the concept of cost distance in determining the distance to market. Cost distance is similar in concept to normal Euclidean distance except that we incorporate the concept of friction to movement. For instance, the paved roads are easiest to travel along, while areas off roads are the most difficult to traverse. We thus need to create a friction map that indicates these impediments to travel. To do so, first create a values file that indicates the frictions associated with each of the surface types we can travel along (based on the road categorizations in KVROADS). Use EDIT to create this real number attribute values file named FRICTION with the following values:

```
0    10.0
1    1.0
2    1.5
4    6.0
5    8.0
```

Save and exit when done.

This indicates that paved roads (category 1) have a base friction of 1.0. Gravel and earth roads (category 2) require 1.5 times as much cost (in terms of time, speed, money etc.). Main trails (category 4) cost 6 times as much to traverse as paved roads while local trails (category 5) cost 8 times as much. Areas off road (category 0) cost 10 times as much to traverse as paved roads. Category 3 (unclassified) has not been included here because there are no roads of this category in our study area.

Now use ASSIGN to assign these frictional attribute values to the KVROADS image. Call the output image FRICTION. Display it with the Quantitative palette to examine the result. Then run the module COST. Choose the cost grow algorithm and specify KVMARK as the feature image and FRICTION as the friction surface image. Use all other defaults. Call the output image COST. When COST finishes, examine the result.

Now use FUZZY to create a standardized factor map called MARKFAC. Display it with the Quantitative palette to examine the result and confirm that the high values (near 255) are those closest to the center of Kathmandu and that the low values (near 0) are those farthest away.

j) The final factor map needed in this stage is the slope factor map. The slope gradients have already been calculated (KVSLOPES). However, our procedure for developing the standardized criterion scores will be slightly different. Instead of using the minimum and maximum values as the control points, use FUZZY with the linear option and base it on values of 0 and 100 (the minimum and a logically determined maximum slope) for control points c and d respectively. Call the output factor map SLOPEFAC. Use DISPLAY Launcher with the Quantitative palette to examine the result and confirm that the high factor scores occur on the low slopes (which should dominate the map).

Weighting the Criteria

Now that the criteria maps have been created, we need to develop a set of weights to establish their relative importance to the objective under consideration. In the procedure that will be used here, the weights will need to be real numbers that sum to 1.0. The factor maps will then be multiplied by their weights and subsequently added together. Since the weights sum to 1.0 and the factor maps all have a standardized range of 0-255, the final weighted linear combination will also have a range of 0-255. At the end of this process, the final suitability map will be multiplied by each of the constraints in turn to *zero out* all excluded areas.

In some cases, it may be feasible to estimate the weights to be used in a multi-criteria evaluation directly. However, many people find this to be somewhat difficult. In addition, when a group of people all have a vested interest in the outcome, it becomes necessary to incorporate the opinions of all participants. For these cases, the procedure of pairwise comparisons associated with the Analytical Hierarchy Process (AHP) is appropriate. In IDRISI, the WEIGHT procedure undertakes this process.

WEIGHT requires that the decision makers make a judgment about the relative importance of pairwise combinations of the factors involved. In making these judgments, a 9 point rating scale is used, as follows:

1/9	1/7	1/5	1/3	1	3	5	7	9
extremely	very strongly	strongly	moderately	equally	moderately	strongly	very strongly	extremely

less important | more important

The scale is continuous, and thus allows ratings of 2.4, 5.43 and so on. In addition, in comparing rows to columns in the matrix below, if a particular factor is seen to be less important rather than more important than the other, the inverse of the rating is used. Thus, for example, if a factor is seen to be strongly less important than the other, it would be given a rating of 1/5. Fractional ratings are permitted with reciprocal ratings as well. For example, it is permissible to have ratings of 1/2.7 or 1/7.1 and so on.

To provide a systematic procedure for comparison, a pairwise comparison matrix is created by setting out one row and one column for each factor in the problem. The group involved in the decision then provides a rating for each of the cells in this matrix. Since the matrix is symmetrical, however, ratings can be provided for one half of the matrix and then inferred for the other half. For example, in the case of the carpet industry problem being considered here, the following ratings were provided:

	WATERFAC	POWERFAC	ROADFAC	MARKFAC	SLOPEFAC
WATERFAC	1				
POWERFAC	1/5	1			
ROADFAC	1/3	7	1		
MARKFAC	1/5	5	1/5	1	
SLOPEFAC	1/8	1/3	1/7	1/7	1

The diagonal of the matrix is automatically filled with ones. Ratings are then provided for all cells in the lower triangular half of the matrix. In this case, where a group was involved, the GIS analyst solicited a rating for each cell from a different person. After providing an initial rating, the individual was asked to explain why he/she rated it that way. The rating and its rationale were then discussed by the group at large, in some cases leading to suggestions for modified ratings. The final rating was then chosen either by consensus or compromise.

To illustrate this process, consider the first few ratings. The first ratings solicited were those involved with the first column. An individual was selected by the analyst and asked the question, "Relative to proximity to water, how would you rate the importance of being near power?" The person responded that proximity to power was strongly less important than proximity to water, and it thus received a rating of 1/5. Relative to being near water, other individuals rated the relative importance of being near roads, near the market and on shallow slopes as moderately less important (1/3), strongly less important (1/5) and very strongly less important (1/8) respectively. The next ratings were then based on the second column. In this case, relative to being near to power, proximity to roads was rated as being very strongly more important (7), proximity to market was seen as strongly more important (5), and slope was seen as being moderately less important (1/3). This procedure then continued until all of the cells in the lower triangular half of the matrix were filled.

This pairwise rating procedure has several advantages. First, the ratings are independent of any specific measurement scale. Second, the procedure, by its very nature, encourages discussion, leading to a consensus on the weightings to be used. In addition, criteria that were omitted from initial deliberations are quickly uncovered through the discussions that accompany this procedure. Experience has shown, however, that while it is not difficult to come up with a set of ratings by this means, individuals, or groups are not always consistent in their ratings. Thus the technique of developing weights from these ratings also needs to be sensitive to these problems of inconsistency and error.

To develop a set of weights from these ratings, we will use the WEIGHT module in IDRISI. The WEIGHT module has been specially developed to take a set of pairwise comparisons such as those above, and determine a *best fit* set of weights that sum to 1.0. The basis for determining the weights is through the technique developed by Saaty (1980), as discussed further in the Help for the module.

k) Run the module WEIGHT and specify to create a new pairwise comparison file. Name the output CARPET and indicate the number of files to be 5. Then insert the names of the factors, in this order: WATERFAC, POWERFAC, ROADFAC, MARKFAC, SLOPEFAC. Hit next and you will be presented with an input matrix similar to the one above, with no ratings. Referring to the matrix above, fill out the appropriate ratings and call the output file CARPET. Hit OK.

You will then be presented with the best fit weights and an indication of the consistency of the judgments. The *Consistency Ratio* measures the likelihood that the pairwise ratings were developed at random. If the Consistency Ratio is less than 0.10, then the ratings have acceptable consistency and the weights are directly usable. However, if the Consistency Ratio exceeds 0.10, significant consistency problems potentially exist (see Saaty, 1980). This is the case with the ratings we entered.

2 *What are the weights associated with the factors on this run? What was the Consistency Ratio?*

l) Since the Consistency Ratio exceeds 0.10, we should consider revising our ratings. A second display will be presented in which inconsistencies can be identified. This next display shows the lower triangular half of the pairwise comparison matrix along with a consistency index for each. The consistency index measures the discrepancy between the pairwise rating given and the rating that would be required to be perfectly consistent with the best fit set of weights.

The procedure for resolving inconsistencies is quite simple. First, find the consistency index with the largest absolute value (without regard for whether it is negative or positive). In this case, the value of -3.39 associated with the rating of the proximity to power factor (POWERFAC) relative to the proximity to water factor (WATERFAC) is the largest. The value -3.39 indicates that to be perfectly consistent with the best fit weights, this rating would need to be changed by 3.39 positions to the left on the rating scale (the negative sign indicates that it should be moved to the left -- i.e., a lower rating).

At this point, the individual or group that provided the original ratings should reconsider this problematic rating. One solution would be to change the rating in the manner indicated by the consistency index. In this case, it would suggest that the rating should be changed from 1/5 (the original rating) to 1/8.39. However, this solution should be used with care.

In this particular situation, the Nepalese group debated this new possibility and felt that the 1.8.39 was indeed a better rating. (This was the first rating that the group had estimated and in the process of developing the weights, their understanding of the problem evolved as did their perception of the relationships between the factors.) However, they were uncomfortable with the provision of fractional ratings -- they did not think they could identify relative weights with any greater precision than that offered by whole number steps. As a result, they gave a new rating of 1/8 for this comparison.

Return to the WEIGHT matrix and modify the pairwise rating such that the first column, second row of the lower triangular half of the pairwise comparison matrix reads 1/8 instead of 1/5. Then run WEIGHT again.

3 *What are the weights associated with the factors in this second run? What is the Consistency Ratio?*

4 *Clearly, we still haven't achieved an acceptable level of consistency. What comparison has the greatest inconsistency with the best fit weights now?*

5 *Again, the Nepalese group who worked with these data preferred to work with whole numbers. As a result, after reconsideration of the relative weight of the market factor to the road factor, they decided on a new weight of 1/2. What would have been their rating if they had used exactly the change that the consistency index indicated?*

Again edit the pairwise matrix to change the value in column 3 and row 4 of the CARPET pairwise comparison file from 1/5 to 1/2. Then run WEIGHT again. This time an acceptable consistency is reached.

6 *What are the final weights associated with the factors? Notice how they sum to 1.0. What were the two most important factors in the siting of carpet industry facilities in the judgment of these Nepalese officials?*

m) Now that we have a set of weights to apply to the factors, we can undertake the final multi-criteria evaluation of the variables considered important in siting carpet industry facilities. To do this, run the module MCE. The MCE module will ask for the number of constraints and factors to be used in the model. Indicate 3 constraints and enter the following names:

SLOPECON

RINGCON

LANDCON

For the names of the factors and their weights, either enter the name of the pairwise comparison file saved from running WEIGHT, i.e., CARPET, or enter the following:

WATERFAC	0.5077
POWERFAC	0.0518
ROADFAC	0.2468
MARKFAC	0.1618
SLOPEFAC	0.0318

Name the output CARPSUIT and run MCE. The MCE module will then complete the weighted linear combination. Display the result. This map shows suitability for the carpet industry. Use "Add Layer" to overlay KVRIVERS and KVROADS. Note the importance of these factors in determining suitability.

7 *MCE uses a procedure that multiplies each of the factors by its associated weight, adds the results, and then multiplies this sum by each of the constraints in turn. The procedure has been optimized for speed. However, it would also have been possible to undertake this procedure using standard mathematical operators found in any GIS. Describe the IDRISI modules that could have been used to undertake this same procedure in a step-by-step process.*

The Multi-Criteria Evaluation for Agriculture

In the above section, we developed a map indicating the suitability of land for the carpet industry. In this section, we will undertake the same process for agriculture. If you recall, the purpose is to determine the suitability of land for agriculture in order to zone the best lands for protection of its agricultural status. The Nepalese group that worked on this problem felt that the same three constraints would apply in the multi-criteria evaluation of agricultural suitability. However, they identified only the water, slope, and market factors as being of relevance to this problem. In addition, they felt that an additional factor needed to be added -- soil capability. Our first step will therefore be to create this new standardized factor map. Then we will follow a similar procedure to that above to create the agricultural suitability map.

n) Display the map KVLANDC with the Qualitative palette and a legend. This land capability map combines information about soils, temperature, moisture, and irrigation potential. Based on the information in the legend (see the beginning of this exercise for detailed descriptions of the categories), the group of Nepalese officials who worked with these data felt that the most capable soil was IBh1R, followed in sequence by by IBh1, IIBh2st, IIIBh, IVCp, and IVBh.

To reclassify the land capability map into an ordinal map of physical suitability for agriculture, use EDIT to create an integer attribute values file named TMPVAL. Then enter the following values to indicate how classes in the land capability map should be reassigned to indicate ordinal land capability:

1	4
2	3
3	2
4	1

5 5

6 6

Next, run ASSIGN and use KVLANDC as the feature definition image to create the output image TMPSOIL using TMPVAL as the attribute values file of reassignments. Then run STRETCH with a simple linear stretch using the minimum and maximum as scaling points to create a standardized factor map called SOILFAC.[50] Display the result with the Qualitative palette.

o) This now gives us the following constraints and factors to be brought together in the multi-criteria evaluation of land suitability for agriculture:

Constraints

SLOPECON

RINGCON

LANDCON

Factors

WATERFAC

SLOPEFAC

SOILFAC

MARKFAC

Here is the lower triangular half of the pairwise comparison matrix for the factors as judged by the Nepalese decision team:

	WATERFAC	SLOPEFAC	SOILFAC	MARKFAC
WATERFAC	1			
SLOPEFAC	1/7	1		
SOILFAC	1	5	1	
MARKFAC	1/6	1/3	1/6	1

Now use the WEIGHT and MCE procedures as outlined in the carpet facilities suitability section to create an agricultural suitability map. Call the pairwise comparison file AGRI and the final agricultural suitability map AGSUIT.

8 What were the final weights you determined for the factors in this agricultural suitability map? What was the Consistency Ratio? How many iterations were required to achieve a solution?

50. There is some question about the advisability of using ordinal data sets in the development of factor maps. Factor maps are assumed to contain interval or ratio data. The standardization procedure ensures that the end points of the new map have the same meaning as for any other factor -- they indicate areas that have the minimum and maximum values within the study area on the variable in question. However, there is no guarantee that the intermediate values will be correctly positioned on this scale. Although in this particular case it was felt that classes represented fairly even changes in land capability, input data of less than interval scaling should, in general, be avoided.

Be sure to examine the final map with DISPLAY Launcher.

Solving the Single-Objective Problems

The original planning problem was to develop a zoning map that would set aside 6000 hectares of specially protected agricultural land and 1500 hectares of land for further expansion of the carpet industry. Let's first consider how to approach these as single objective problems. In the next part, we will look at how to resolve the conflicts between the objectives, a multi-objective problem, and arrive at a final solution..[51]

If we consider either of these objectives on their own, we are clearly quite close to a final solution. For example, in the case of the carpet industry objective, we already know the comparative suitability of the land for this use. We only need to figure out which are the *best* 1500 hectares! To do this, we need to rank order the data cells in terms of their suitability, and select as many of the most highly ranked cells to total 1500 hectares. We will do this with a combination of the RANK and RECLASS modules.

p) Run the module RANK and indicate that you wish to rank order the CARPSUIT image. You will need to indicate whether you wish to use a second image to resolve ties. (Quite frequently, data cells will have the same level of suitability for a given objective. For these situations, we can choose to either establish a rank order arbitrarily, or look at the cell values in question on another image to determine their rank order.) In this case, we can choose the other objective's suitability map as the basis for resolving ties. By doing so, we can resolve ties in suitability for the carpet industry by giving higher rank to cells that are less suitable for agriculture.[52] Therefore specify AGSUIT as the secondary sort file to use in resolving ties. Call the output image to be produced CARPRANK. Choose ***descending*** ranks (i.e., the cell with the highest suitability value will have the lowest rank number -- 1) for the output image's sort order and ***ascending*** ranks for the secondary sort.

9 *Examine CARPRANK with DISPLAY Launcher. What are the minimum and maximum values in the image? What is the relationship between the maximum value and the size (in rows and columns) of the image?*

q) Now that the carpet industry suitability map has been rank ordered, any number of the best cells can be isolated using RECLASS. In the case here, we wish to isolate the best 1500 hectares of land. However, since CARPRANK has values that indicate ranks, we will need to convert this area into a specific number of cells. In this data set, each cell is 30 meters by 30 meters. This amounts to 900 square meters, or 0.09 hectares per cell (since a hectare contains 10,000 square meters). As a result, 1500 hectares is the equivalent of 16,666 cells.

Run RECLASS and indicate that you wish to reclassify CARPRANK to create BESTCARP. Use the default user-defined classification option and indicate that you wish to assign a 1 to all values from 1 to 16667 and a value of 0 to all values from 16667 to 999999 (i.e., all other values). Then display the result. You may wish to use "Add Layer" and the advanced palette selection to overlay the KVRIVERS file with a BLUE symbol file and the KVROADS file with a GREEN symbol file.

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51. Note particularly, however, that this process of looking at the problem from a single-objective perspective is not normally undertaken in the solution of multi-objective problems. It is only presented here because it is easier to understand the multi-objective procedure once we have examined the problem from a single-objective perspective.

52. The sort order of the secondary ranks should be chosen with direct reference to the decision problem at hand. In this case, we have competing objectives. As a result, the best choices for any objective will be cells that are strongly suitable for the objective in question and strongly unsuitable for the other objectives. This will be achieved by choosing a sort order for the secondary ranks that is opposite to the order of the primary ranks. In cases where objectives are not competing, but complementary (such as with multiple use land use planning problems), it would be better to make the secondary sort order identical to that used for the primary ranks.

r) Now use the same procedure as that just described to create AGRANK from AGSUIT (with descending ranks) using CARPSUIT as the secondary sort image (using an ascending secondary sort order). Then use RECLASS to create a map named BESTAG from AGRANK that isolates the best 66,666 cells (which is the equivalent of 6000 hectares). Use the module CROSSTAB to produce a cross-classification image of BESTCARP against BESTAG. Call this cross-classification image CONFLICT. Then display the result to examine the CONFLICT image. Indicate that you wish to use a legend.

10 *Which class shows areas that are best suited for the carpet industry and not for agriculture? Which class shows areas that are best suited for agriculture and not for the carpet industry? Which class shows areas of conflict (i.e., were selected as best for both agriculture and the carpet industry)?*

The conflict image thus illustrates the nature of the multi-objective problem with competing objectives. The ultimate solution still needs to meet the area targets set (1500 hectares of land for the carpet industry and 6000 hectares of land for agriculture). However, since land can only be allocated to one or the other use, conflicts will need to be resolved.

A Solution for Conflicting Objectives

The solution to the multi-objective problem presented here requires a procedure that is specific to the case of competing objectives. As we have already seen, there is more than one way in which this may be solved. However, the solution to be discussed next is perhaps the most common -- a case where we have no basis for prioritizing land allocation, and we therefore must resolve conflicting claims for territory on a location-specific basis.

MOLA (an acronym for Multi-Objective Land Allocation) solves this problem with a procedure that simply requires ranked suitability maps for each of the objectives being considered. MOLA then undertakes the iterative process of:

1. reclassifying the ranked suitability maps according to the area targets for each objective;
2. resolving conflicts using a *minimum distance to ideal point* rule based on weighted objectives;
3. checking how far short of the area targets each objective is, and then
4. rerunning the procedure until a solution is reached.

By using ranked suitability maps as inputs, MOLA not only makes use of a simple decision heuristic for finding the best areas for any given objective, but also standardizes the objectives (using what amounts to a histogram equalization transform) in order to make them comparable before any weights are applied.

s) Run HISTO to examine the histogram of suitability maps in CARPSUIT. Since 0 represents areas masked out by the constraints (and thus not of interest to us), indicate that you wish to use a minimum value of 1 and a maximum value of 255. Choose a class width of 1 and graphic output.

11 *How would you describe the shape of this distribution?*

t) Now run HISTO again to look at a histogram of suitability maps in AGSUIT. Again indicate that you wish to use a minimum value of 1 and a maximum value of 255. Choose a class width of 1 and graphic output.

12 *How would you describe the shape of this distribution?*

Clearly, neither of these distributions is normal in character (i.e., taking the shape of a bell-shaped curve). Had it been the case that both distributions were normal, we could have used the most familiar form of standardization that is intended to match distributions -- conversion of measurements to z-scores (also known as *standard scores*). In those cases where the distributions are normal, the mean and standard deviation are calculated and used as follows:

$z = (x - m) / s$ *where:* z = standard score
x = a measurement
m = mean
s = standard deviation

When all values are transformed in this fashion,[53] the resulting data set has a mean of 0 and a standard deviation of 1. The procedure is thus a position matching and scaling operation that allows normal distributions to be compared. However, it does assume that the distributions are in fact normal -- a condition that is not found here, and one that is often lacking in geographical data sets. As a result, we will need to match the histograms by a non-parametric technique known as *histogram equalization*.

Histogram equalization is explicitly provided in IDRISI by the STRETCH module. However, as mentioned in the introduction, it is also the result of the RANK process.[54]

u) Use HISTO to look at CARPRANK. Use a class width of 4000 and use all other defaults. Then do the same for AGRANK.

13 How do these histograms appear?

Note that the last class has a lower frequency. This arises simply because of the minimum and maximum specified for the output graph.

v) Now to complete the multi-objective decision process, run the module named MOLA. Input the number of objectives to be considered -- specify 2 -- and the name for the output image -- specify FINAL1. You next need to specify the area tolerance to be used in solving the problem. This will allow the procedure to stop when it is within that many cells of the final result. Enter 166 in order to have it stop as soon as it is within 15 hectares of the desired solution.

Users will also need to indicate the names of the objectives, the weight to assign to each objective, the ranked suitability maps affiliated with the objectives, and the areas allocated to each. Enter "Carpet" for the first objective caption and give it a weight of 0.5. Enter CARPRANK as the rank map affiliated with the first objective and 16666 cells (i.e., 1500 hectares) as the areal requirement. Press the forward arrow to input the second objective caption. Enter "Agriculture" and give it a weight of 0.5 so that the weights of the first and second objectives have equal weight in this solution. Indicate AGRANK as the rank map affiliated with the second objective and specify 66666 cells (i.e., 6000 hectares) as the areal requirement. It will then go through the iterative solution.

14 How many iterations did it take to achieve a solution? How many hectares of each objective were eventually allocated? Be sure to examine FINAL1.

w) Now run the MOLA procedure again but specify a zero-tolerance solution (i.e., an exact solution). Call this result FINAL2.

53. A module named STANDARD exists in IDRISI to simplify this procedure. It automatically calculates the mean and standard deviation and applies the transformation.

54. There is a difference in the histogram equalized output produced by STRETCH and RANK. With RANK, a very strict histogram equalization is produced. In addition, the number of classes in the output is equal to the number of input cells. Using STRETCH with histogram equalization, the number of output classes can be set at any value. In addition, input cells having the same value will not be split between classes in order to meet the needs of histogram equalization. Thus the resulting image will not be perfectly histogram equalized.

15 *How many iterations did it take to achieve an exact solution?*

16 *Looking at FINAL2, how geographically coherent do you find the areas selected for the carpet and agriculture industries? (i.e., do these tend to be very small and fragmented or do they cohere into larger regions?)*

17 *Display FINAL2 and use "Add Layer" to overlay the roads (KVROADS) with the GREEN user-defined symbol file and the rivers (KVRIVERS) with the WHITE user-defined symbol file. What evidence can you cite for the procedure appearing to work?*

Conclusions

The procedure illustrated in this exercise provides both immediate intuitive appeal and a strong mathematical basis. Moreover, this choice heuristic procedure highlights the participatory methodology employed throughout this workbook. The logic is easily understood and as the procedure offers an excellent vehicle for discussion of the identified criteria and objectives and their relative strengths and weaknesses.

It isolates the decisions between competing objectives to those cases where the effects of an incorrect decision would be least damaging -- areas that are highly suitable for all objectives.