Wetlands Management using GIS and Multi-Criteria Evaluation Tools

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Demonstrating a multi-criteria evaluation (MCE) decision-making tool using geographical information systems (GIS) is the main objective of this chapter. We use wetlands management as an example of the complex spatial decision-making process involving tradeoffs. Wetlands are an integral part of the world's ecology and, therefore, their management needs to be given high priority. However, due to man-made changes, especially with large-scale urban developments, many wetlands are now in a fragmented condition that is preferably avoided. Modern technology, which includes remotely-sensed satellite data and GIS have excellent capabilities for studying and analysing the spatial issues regarding wetlands management. This chapter demonstrates the use of Fuzzy logic map overlays for MCE as an attractive alternative to weighted linear combination and Boolean map overlays commonly used in GIS analysis.

13.1 Introduction

Wetlands are transitional areas between aquatic and terrestrial ecosystems where the water table is usually at or near the surface or the land is covered by shallow water. They include marshes, flood plains, bogs, peat lands, shallow ponds, littoral zone of large water bodies, tidal marshes etc. Besides providing habitats for a gamut of fauna and flora they carry out a crucial role as breeding grounds for fish and other aquatic life. Wetlands serve as important life support

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systems by helping in flood control, recharging ground water, regulation of hydrological regime and in reduction of sediment load as well as pollution.

Due to rapid development of many urban/rural areas, the encroachment of wetlands is a common problem. The types of development pressures include urban sprawl, agricultural and rural development, increased groundwater usage, transportation and tourism. Both citizens and decision-makers now recognize the importance of conflict resolution process when development affects nature adversely. While the problem may not have a solution that satisfies all users and objectives, a well-informed and open decision making process is demanded by all.

Geographical information systems (GIS) is a relatively new technology used in decision making. GIS provides visual and non-visual means of keeping a diverse and large amount of data such as digital elevations, soil types, flora and fauna, land usage, transportation corridors, rivers and lakes within a consistent geographic analysis framework. Each layer of a GIS keeps one type of data (for example transportation corridors or rivers) in a map form. By overlaying the various maps one gets a full picture of the area under study. See Figure 13.1 for example, which presents a small segment of Grand River Conservation Area (GRCA) between Kitchener-Waterloo and Guelph showing the existing transportation corridor (Highway 7 between the Kitchener and Guelph) and various wetlands, rivers, and lakes. In the figure, curves with darker shaded buffer zones indicate rivers and close by areas near rivers that are environmentally sensitive. The straighter lines with lighter shaded buffer zones indicate roads

Figure 13.1 Map of GRCA area between Kitchener-Waterloo and Guelph.

and adjacent areas that are more preferable for development. Only some segments of roads and rivers are shown for clarity. Other dark patches indicate wetlands and grey patches indicate urban areas.

Multi-criteria evaluation (MCE) in any decision-making process is a practical necessity. For example, for the simple problem having the single objective of siting a family home, one may have two criteria, for example, the distance from parks and the distance from downtown, both of which one would like to minimize. Examples of objectives include minimizing cost, maximizing usable floor space.

The common MCE methods using GIS are Boolean overlays and weighted linear combinations of map overlays. The Boolean map overlay provides a hard AND which could be very conservative or an OR which could be over-optimistic. On the other hand, the method of weighted linear combinations of map overlays uses a linear transformation so that values of each of the map layers are normalized to the same range, for example, zero to one. But this linear transformation may be too simplistic (Jiang and Eastman, 2000). To overcome these difficulties a fuzzy logic method is suggested. This method will be explained later and its suitability discussed for the problem of wetlands management.

13.2 Wetlands and their Management

The definition of wetland as per the United Nations Convention on Wetlands of International Importance (Davis, 1994) is:

“Areas of marshes, fens, peatlands or water whether natural or artificial, permanent or temporary with water, i.e., static or flowing, fresh, brackish or salt including areas of marine water, the depth of which at low tide does not exceed six meters.”

This definition gives water depth in case of marine areas not to exceed six meters but it is silent about other aquatic bodies. As such it becomes difficult to classify other aquatic bodies into the wetland group. In order to prepare a status of wetlands in the United States, the U.S. Department of Interior Fish and Wildlife Service Authority adopted the following definition of Cowardin (1979):

“The wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water.”

For the purpose of this classification, wetlands must have one or more of the following attributes:

- at least periodically the land supports predominantly hydrophytes;
- the substrate is predominantly undrained hydric soil; and

- the substrate is non-soil and is saturated with water or covered by shallow water sometime during the growing season of each year.

13.3 Management Issues

The following factors affect wetlands and should be considered during development: encroachment (from urban sprawl, rural/agricultural transformations, and transportation), siltation and soil erosion (Barr, 1998), weed infestation, pollution (through pesticides and fertilizers, sewers, and industrial waste), and aquaculture

The combined threat of these above factors have given rise to the following problems: decreased biological diversity particularly endemic and endangered species, deterioration of water quality, sedimentation and shrinkage in the area, decrease in migratory bird population, fish and other faunal productivity, and prolific growth of obnoxious aquatic weeds. Because wetlands and their management have a spatial dimension, and the extent of development pressure on wetlands can be analyzed spatially, it is thus convenient and important to use GIS to help in decision-making.

13.4 Use of GIS for Wetlands Management

GIS can bring together physical, environmental and socio-political information, presenting data in an accessible form for all stakeholders in the area. The key functions of a complete GIS modeling and decision-making tool are:

- Organizing temporally and spatially varying information on conflicting and changing land and water uses and inputs within the system, allowing environmental managers to monitor the system as a whole rather than at fixed locations.
- Assisting planners to take decisions on development plans rationally on the basis of a land capability assessment. Maps of vulnerability to ground water pollution and overdraft will help educate local farmers so that they will be able to appreciate and react to the suggested plans for development.
- Providing an invaluable educational tool, allowing the various up and down stream stakeholders to visualize the effect of their actions both on other users and the system as a whole. A visual tool of this nature is also important in an area of low literacy, and

potential conflict between different stakeholders. GIS has proved elsewhere to be a key pedagogic tool in involving people in the management of their wider environmental system (Harris et al, 1995).

- Identifying potential protection strategies for particularly sensitive areas or habitat zones, which could be 'tested', and management scenarios examined using the model without the expense of a field trial.

13.5 Multi-Criteria Evaluation Tool

A multi-criteria evaluation tool (MCET) is necessary to analyze various management alternatives that trade off developmental activities against the protection of wetlands. Examples of criteria include proximity to wilderness, proximity to highways, soil condition, sustainability indicators, and cost. Decision makers, who may have different priorities and values, will value the same criterion differently. MCET will help aggregate the decision maker's choices by using fuzzy logic analysis to overcome the problems for non-crisp values and boundaries and uncertainty. The expected end results from MCET are: (i) various alternatives based on multiple objectives and multiple criteria, (ii) scientifically based aggregation, and (iii) spatial choices clearly understandable to all decision makers. The results in the next section illustrate points (ii) and (iii).

A simple question to ask may be "What areas are suitable for a given objective, such as, housing development or new transport corridor?" Suppose we have two people each choosing their own area of choice (darker shaded top right rectangle or lighter shaded bottom left rectangle in Figure 13.2) for a given objective. Then it is simple to apply Boolean logic (AND) to find the area that both like as in the rectangle in the middle of the figure in Figure 13.2.

Figure 13.2 Finding a suitable area acceptable to two decision makers.

Unfortunately real-world problems are much more complicated as listed below:

- the boundaries possibly are not crisp, that is, people may prefer values not just *suitable* or *not suitable* but rather *somewhat suitable*, *suitable*, *somewhat not suitable*,
- there may be many people (or more layers), and
- the major problem is how to aggregate these “fuzzy” data and provide a suitable area to meet our objective.

The Fuzzy Logic Model solves this problem rather nicely using the fuzzy member functions and fuzzy operators. Determining the weights for each layer may be an additional problem and will have to be “extracted” from various decision makers and, to limit the scope of this chapter, is assumed to be known.

13.6 Fuzzy Logic and Fuzzy Logic Operations

The three important components of fuzzy logic method are: fuzzification, aggregation, and defuzzification. Fuzzification involves assigning a membership function value (see Ponnambalam and Mousavi (2000) for further details) to each pixel (raster) in the map. Fuzzification or clustering can also be done with expert knowledge. An example of fuzzification: Should a man with a height of 1.65 m be considered of medium height or tall? Fuzzy membership function gives shades of medium or tall depending upon the viewpoint of the decision maker. In our problem of wetlands management, the various map layers (wetlands, transportation distances, urban areas, rivers, etc) each will have some appropriately chosen membership function. A relevant example will be provided in the next section. *Aggregation* of various fuzzy sets is based on Fuzzy operators such as min, max, product, gamma function, etc. We provide a few examples below (Bonham-Carter, 1994) where μ_i is the membership function value of i^{th} map layer:

Fuzzy AND Operator: $\mu_{Combination} = \min_i \mu_i$

The above operator is equivalent to Boolean AND for classical Boolean values of just 0 or 1. The result of the fuzzy operator is affected by the smallest value and hence is also conservative.

Fuzzy OR Operator: $\mu_{Combination} = \max_i \mu_i$

The above operator is equivalent to Boolean OR for classical Boolean values of just 0 or 1. The result of the fuzzy operator is affected by the largest value and hence is overoptimistic.

Fuzzy Algebraic Product: $\mu_{Combination} = \prod_i \mu_i$

The above operator can produce very small values for the combined map as even a small value of single map can affect the result.

Fuzzy Algebraic Sum: $\mu_{Combination} = 1 - \prod_i (1 - \mu_i)$

The above operator is complementary to the fuzzy algebraic product and tends to reinforce values if maps have similar systems.

And lastly, *Fuzzy Gamma Operation:*

$$\mu_{Combination} = (Fuzzy\ Algebraic\ Sum)^\gamma (Fuzzy\ Algebraic\ Product)^{1-\gamma}$$

where:

$$0 < \gamma < 1.$$

The results we discuss in the next section use this aggregation operator with $\gamma = 0.05$.

Recall that the above operations are carried out pixel by pixel. The last component is the *defuzzification* module, which, as the name suggests, reduces a fuzzy membership function value to a crisp value. In our problem, we did not require this step and instead the combined fuzzy membership value of 0 to 1 is directly mapped and conclusions drawn from this map.

13.7 Case Study

In Figure 13.1 (presented earlier) we show part of the Grand River Conservation Authority (GRCA) landuse map between the cities of Kitchener-Waterloo bottom left corner) and Guelph (top right corner), with wetlands (the many dark patches), parts of Grand river and others (curves), and the current Highway 7 between the two cities (the straight line between the cities) and parts of some other main roads.

Figure 13.1 depicts only selected buffer zones around both river and road features. But for calculation of the final map the buffer zones were calculated for the entire area of importance. It is tempting to use the buffer zones directly to decide what areas are suitable for development, which, in this case will be the white areas outside the buffer zones. However, this map will be considered to be the base case map. Generating a map that represents a hypothetical decision-maker's preferences with respect to the different criteria will be our next objective.

For simplicity we restrict our case to a single decision maker who is pro-environment. This decision maker's objective is to prevent urban sprawl (no new areas beyond what is already identified as urban) and zero encroachment of known wetlands. S/he will also prefer that development take place only along the existing corridors of roads with decreasing preference the further a point is from these roads. An opposite view is taken by this decision maker regarding rivers: s/he prefers development to be as far as from them as possible. Therefore, the membership function for the four different layers will reflect this decision maker's preferences.

For simplicity, we will assume an impulse type membership function for the urban layer (that is, a crisp value of 1 for existing urban lands acceptable for development and zero otherwise), and also an impulse type function for the wetlands layer (that is, a crisp value of 0 for existing wetlands which means not acceptable for development and one otherwise). This of course is the choice of this particular decision maker. A decision maker may have fuzzy membership criteria such as exponentially declining function development acceptability with respect to roads with 1 for locations immediately adjacent to the road and 0 for locations far away. Similarly a decision maker could have an S-type fuzzy membership function for proximity to rivers layer with zero value for development acceptability when immediately adjacent to a river increasing to a value of 1 when far away from the river. The decision maker can modify the shape of these functions to suit his or her preferences. Figure 13.3 presents map overlay based on the fuzzy logic method for this decision maker's choice for membership functions. The areas with higher values, that are closer to 1 (lighter the better), are considered by this decision maker as *suitable* for development while the areas with values close to 0 are considered as *unsuitable* for development. The shades indicate that some areas are *somewhat suitable*, to *moderately suitable*, to *not so suitable*. Similar maps can be produced for each decision maker or stakeholder and they can be further aggregated using the fuzzy logic operators to produce a single map. Depending upon the operator and operator parameters a large number of alternatives can be produced which then can be used in a forum for an informed decision making. The example we presented uses wetlands management as an example but the same methodology can be used for other problems such as location of pipelines or bridges or developing theme parks or industrial areas or landfill site location. The major disadvantage of the proposed method is the large data requirements for the various map layers and the need to use expensive software for their manipulations, as well as the required training for using such software effectively. Figure 13.1 was produced using the software ArcView Version 8 (www.esri.com). MATLAB Version 6 (www.mathworks.com) was used for assigning membership function values for each pixel and for fuzzy aggregation and was used to produce Figures 13.2 and 13.3.

Figure 13.3 Fuzzy logic map overlay using a single decision maker's preferences. (0 - unsuitable and 1 - suitable).

13.8 Conclusion

Many problems in the real world are “spatial” in nature and can be modeled well by GIS. But decision making is complicated by nonexact or noncrisp nature of criterion as well as these spatial features. GIS combined with the Fuzzy Logic method is a powerful multi-criteria and multi-objective decision making tool. Gaining cardinal or ordinal weights for each criterion from each user is problematic but generation of alternatives for the use of Decision Maker can be achieved easily with these tools and solutions presented in easy-to-understand graphic displays.

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