Original Article

The use of GIS and multi-criteria decision-making as a decision tool in forestry

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Abstract Geographical information systems (GIS) provide forest managers with tools to use in planning forest operations by allowing them to visualize and integrate data into the planning decisions. As the forest planning process becomes increasingly complicated, there is a need to assist forest planners with operative tools. The combined use of GIS and multi-criteria decision methods (MCDM) allows forest managers to visualize solutions proposed by MCDM and to have a better understanding of the problem they confront. The main purpose of this paper is to show the integration of GIS and the analytic hierarchy process for forest firefighting planning.
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Keywords: geographical information systems; forest management; multi-criteria decision analysis; multi-criteria decision methods; analytic hierarchy process; spatial multi-criteria decision-making

Introduction

Various problems encountered in life can be classified as multi-criteria decision-making problems. Multi-criteria decision-making problems can be either discrete or continuous (Vassilev *et al*, 2005). The techniques used in the different approaches of decision analysis are called multi-criteria decision methods (MCDM). Since their emergence, multi-criteria analyses have been used largely to deal with spatial decision problems.

This paper aims to show the integrated use of geographical information systems (GIS) and the analytic hierarchy process (AHP) in firefighting planning. This integration is shown as a prototype application. In the application section, the problem is handled as a spatial multi-criteria decision-making problem. Different criteria can be used to evaluate the effectiveness/ineffectiveness of the study area in struggling with forest fires. In this study, only 'distance from water resources', 'distance from streams' and 'distance from settlement areas' criteria were used, as only maps of these criteria could be constituted with the data obtained from the study area.

This study focuses on firefighting planning from the strategic-planning perspective. By identifying the most effective areas, the ineffective areas in struggling with forest fires can also be determined. Therefore, in case of a forest fire, the effective/ineffective areas can be visually identified, and resources can be allocated properly according to the predefined set of criteria. The result of this study can give new insights to the forest manager for the long-term planning of allocating resources.

Analytic Hierarchy Process

Multi-criteria decision-making problems can be divided into two distinct classes. In the first class of problems, a finite number of alternatives are explicitly given in a tabular form. These problems are called discrete multi-criteria decision-making problems or multi-criteria analysis problems. In the second class, a finite number of explicit set of constraints in the form of functions define an infinite number of feasible alternatives. These problems are called continuous multi-criteria decision-making problems or multi-criteria optimization problems (Vassilev *et al*, 2005).

Pair-wise comparisons, ranking methods and rating methods are some of the methodologies used in multi-criteria decision-making. The pair-wise comparison technique is based on the method called the AHP, a decision-making technique developed by mathematician Thomas L. Saaty. It is an eigenvalue approach to the pair-wise comparisons and is based on building hierarchy of criteria, and at each node of hierarchy, weighting is performed (Saaty, 1980, 1986).

The AHP consists of three main operations: hierarchy construction, priority analysis and consistency verification. The decision-makers need to break down complex multiple criteria decision problems into their component parts. This

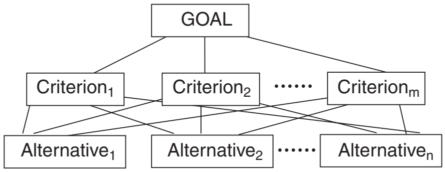

Figure 1: The basic hierarchy structure in AHP.

approach allows the decision-maker to structure problems in the form of a hierarchy. Figure 1 shows the basic hierarchy structure in AHP.

After the hierarchy structuring, the decision-makers have to compare each element in the same level in a pair-wise fashion (Ho, 2008; Liberatore and Nydick, 2008).

Some key and basic steps involved in this methodology are as follows (Saaty, 1980; Vaidya and Kumar, 2006):

1. Stating the problem.
2. Broadening the objectives of the problem or considering all factors, objectives and their outcomes.
3. Identifying the criteria of the problem.
4. Structuring the problem in a hierarchy of different levels constituting goal, criteria, sub-criteria and alternatives.
5. Comparing each element (pair-wise comparisons) in the corresponding level and calibrating them on the numerical scale. The scale has values ranging from 1 to 9, as shown in Table 1 (Saaty, 1980).
6. Performing calculations to find the maximum eigenvalue (λ), consistency index (CI), consistency ratio (CR) and normalized values for each criteria/ alternative. λ represents average value of the consistency vector, CI provides a measure of departure from consistency and CI and CR are calculated as shown in formula 1 and formula 2, respectively:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{1}$$

$$CR = \frac{CI}{RI} \tag{2}$$

   RI is the random index and depends on the number of elements being compared, as shown in Table 2 (Saaty, 1980).
   If $CR < 0.10$, the ratio indicates a reasonable level of consistency in the pair-wise comparison; however, if $CR \geqslant 0.10$, the values of the ratio indicates inconsistent judgements.

Table 1: Scale for pair-wise comparisons

Intensity of importance	*Definition*
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to extremely strong importance
9	Extreme importance

Table 2: Random inconsistency indices (*RI*) for n=1, 2, …, 15

n	*RI*	*n*	*RI*	*n*	*RI*
1	0.00	6	1.24	11	1.51
2	0.00	7	1.32	12	1.48
3	0.58	8	1.41	13	1.56
4	0.90	9	1.45	14	1.57
5	1.12	10	1.49	15	1.59

7. If the maximum eigenvalue, *CI* and *CR* are satisfactory, then decision is taken based on the normalized values; otherwise the procedure is repeated until these values lie in a desired range.

Geographical Information Systems

Environmental management has been a main motivator of developments in GIS. When these systems were first developed in the early 1960s, they were no more than a set of innovative computer-based applications for map data processing. But GIS grew very fast and became an important element of information technology (Franklin, 2001; Lo and Yeung, 2002).

As stated by Kleynhans *et al* (1999), the development of GIS technology makes it possible to compile, store, retrieve, analyse and display vast quantities of spatial data. Although the use of GIS is expanding day by day, its most important applications include those that support decision-making.

GIS technology offers the combined power of both geography and information systems and provides ideal solutions for effective natural resource management (Shamsi, 2005). This technology integrates common database operations such as query and statistical analysis with visualization and geographic analysis offered by maps. These abilities distinguish GIS from other information systems and make it valuable for several applications (Lang, 2001). The first studies involving an integration of GIS–multi-criteria analysis integration were in the late 1980s and early 1990s (Chakhar and Martel, 2003).

Forest Management

Forestry involves the management of a wide range of natural resources, such as grazing land and water supplies, as well as timber. Forest management includes management of harvesting and recreational areas and protection of endangered species and archaeological sites. Forest management decisions usually involve multiple criteria and multiple objectives (Aronoff, 1995; Kazana *et al*, 2003; Mohren, 2003).

The amount of data and information involved in the forest management process is often overwhelming. Integrated decision support systems help forest managers to make consistently effective decisions about forest ecosystem management (Potter *et al*, 2000). Compared with previous forest management approaches, new forest management strategies require integration of spatial information technologies, such as GIS, remote sensing and decision support systems (Franklin, 2001).

The forest database design is crucial in forest management. The data should be accurate, properly organized and detailed, and should be able to be obtained easily. The gathering of spatial and non-spatial data and the analysis determine the quality of forest management. Martell (1982) provides a comprehensive review of OR approaches in forest-fire management. Forest management consists of several components, and a fire management system is one of these. It is very important to minimize damage caused by forest fire, and this can be achieved by developing an efficient fire management system.

Firefighting planning is a central component of a fire management system. It is very important to determine and visualize the areas that are effective or ineffective in firefighting planning. One way of achieving this is by using GIS and AHP, and visualizing the results on a digital map. It will be possible to take proactive measures and transfer resources to the ineffective areas according to results of analyses represented on a digital map.

GIS and Multi-Criteria Decision-Making Integration

Spatial multi-criteria decision problems typically involve a set of geographically defined alternatives from which a choice of one or more alternatives is made with respect to a given set of evaluation criteria. Spatial multi-criteria analysis differs from conventional multi-criteria decision analysis (MCDA) in that it requires information on the criterion values and the geographical locations of alternatives. The results depend not only on the geographical distribution of attributes but also on the value judgements of decision-makers (Jankowski, 1995; Malczewski and Ogryczak, 1996). As stated by Carver (1991) and Jankowski (1995), two important components of spatial MCDA are GIS and multi-criteria decision-making.

Many spatial decision problems lead to the integration of GIS and MCDA, as these two techniques can interact with each other. GIS techniques have an important role in analysing decision problems and are decision support systems that integrate spatially referenced data into a problem-solving environment. MCDA provides many techniques and procedures for structuring decision problems and for evaluating and prioritizing alternative decisions. The integration of GIS and multi-criteria decision-making can be thought of as a process that combines geographical data and value judgements of decision-makers to obtain information for decision-making (Malczewski, 2006).

In the context of GIS, two procedures are common for the Multi-Criteria Evaluation (MCE) the Boolean overlay and the weighted linear combination (WLC). In a Boolean approach, all criteria are assessed by thresholds of suitability to produce Boolean maps, which are then combined by logical operators such as intersection (AND) and union (OR). With the use of WLC, continuous criteria (factors) are standardized to a common numeric range and then combined by weighted averaging. The result is a continuous mapping of the suitability (Jiang and Eastman, 2000).

Boolean analysis can only be used when there are two states (criterion satisfied and criterion not satisfied). This analysis was developed by George Boole, who devised rules and methodologies for combining two-states variables. The Boolean search is generally concerned with the 'AND' operator. The logical 'AND' operator produces a true result from the phrase 'A AND B' only if A and B are 'true'. In GIS, this methodology is used in a multiplication overlay between layers containing only zeroes (representing areas where conditions are 'false' or 'criterion is not satisfied') and ones (representing areas where conditions are 'true' or 'criterion is satisfied') (Eastman, 2003).

Materials and Methods

In this study, GIS and multi-criteria decision-making integration was applied for the Izmir Forest Administration's Chief Office, located in western Turkey. Izmir Forest Administration's Chief Office is subordinate to Izmir Directorate of Forest Administration. This institution is divided into eleven forest

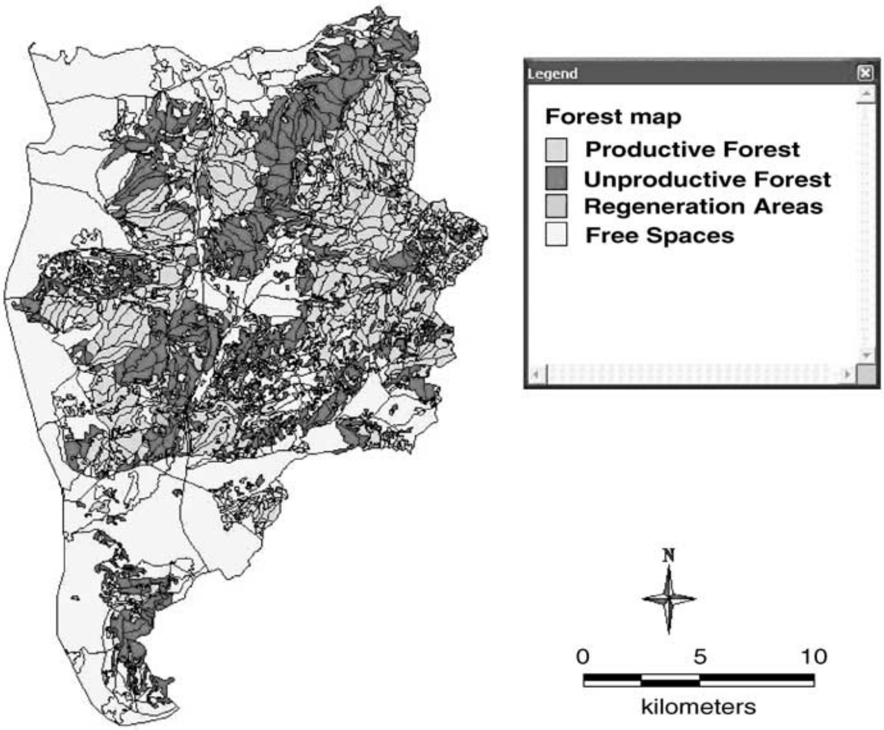

Figure 2: Izmir Forest Administration Chief Office forest boundary map.

administration offices, and our study area, managed by the Izmir Forest Administration's Chief Office, is one of them.

Figure 2 shows the forest boundary map of the Izmir Forest Administration's Chief Office.

The general area is 39 270 ha, and 50.88 per cent of this area is forested land. The total forest area is 19 983.5 ha, of which 11 494.5 ha (57.52 per cent) is productive land and 8489 ha is unproductive.

The main purpose of this study is to show forest managers how to plan firefighting by using GIS and OR. This study is performed to initiate contemporary forest management planning, in contrast to the conventional forest management planning currently in use. Most forest administration chief offices have paper maps and do not regularly maintain and update a forestry database. In contemporary forest management, a forest database must be designed regularly, and all maps must be in digital form. GIS not only enables organization and management of data but also integrates different optimization models, such as OR, into the problem-solving environment. GIS plays a valuable role in transitioning from conventional forest management to contemporary forest management.

There are several criteria that must be considered in the firefighting planning process, such as fuel/vegetation type, soil properties, topographical information, slope, aspect and altitude information, distance from roads, distance from water resources, distance from settlement areas and distance from streams. However, in this study, only the last three criteria were used. This was because maps of the other criteria were unavailable to the authors, whereas maps for the three criteria above could be obtained from the study area. The most important point in using GIS and AHP is the availability of maps of all criteria.

The first phase of the application is the forest database design and transformation of the 'water resources', 'streams' and 'settlement areas' maps into vector-based digital maps. The raw data were obtained from the Izmir Forest Administration's Chief Office. The IDRISI software package was used to carry out the analysis. Water resources were available in the form of coordinates on a map, which were then geo-coded. 'Stream' and 'settlement area' maps were transformed into digital maps. Following this, all vector-based maps were converted to raster-based maps. This conversion was necessary to be able to perform an AHP in IDRISI. A pair-wise comparisons matrix was structured by interviewing the directorates of the fire-combating department of the Izmir Forest Administration's Chief Office.

Water resources and streams are strategic components in fire management. The areas closer to the water resources and streams are considered to be more effective in coping with fire than the areas that are distant from water resources and streams. Settlement areas are important factors to intervene and control fire. To some, however, settlement areas can also be considered a risk factor. In some cases, the regions closer to the settlement areas are more fire-prone because of the human factor.

Results and Discussion

In this section, the results of the analysis are presented in detail. The next section discusses how the distance maps of all criteria were structured.

'Distance from water resources' factor, 'distance from streams' factor and 'distance from settlement areas' factor

There are four water resources in the area under study. The 'water resources' map was derived by using the module DISTANCE in IDRISI software package,

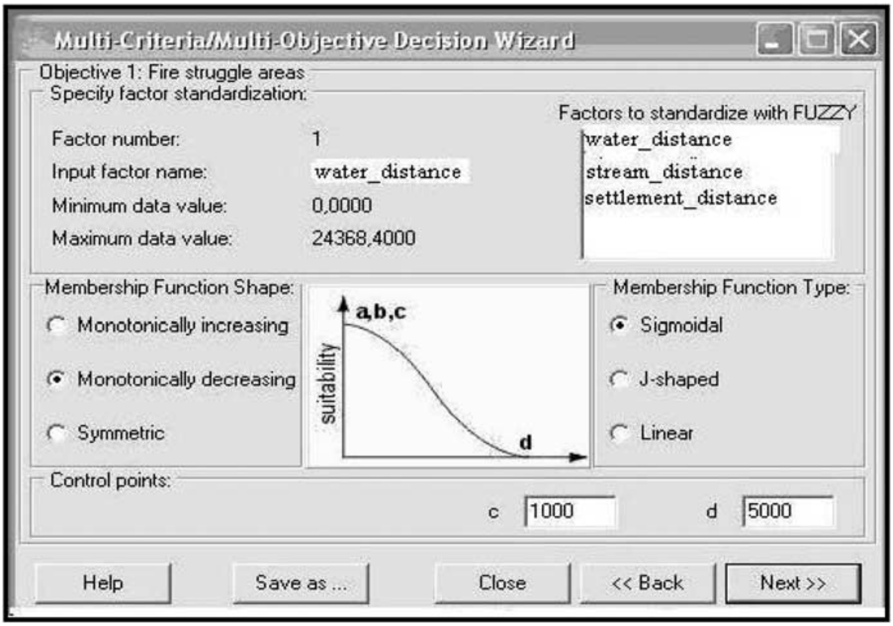

Figure 3: Fuzzy standardization process for distance map of water resources.

as a result of which the distance image, which shows a simple linear distance from all water resources in our study area, was obtained. The same procedures were followed to obtain distance maps of 'streams' and 'settlement areas' factors.

As discussed in interviews with the directorates of the fire-combating department of the Izmir Forest Administration's Chief Office, the areas that have a distance of less than 5000 m to water resources were considered effective, whereas those with a distance equal to or beyond 5000 m were considered ineffective in fighting forest fires. The suitability (effectiveness) decreases when the distance increases. For this reason, a monotonically decreasing option was selected, as shown in Figure 3.

The areas that have a distance less than 5000 m from the streams were considered effective, whereas those with a distance equal to or beyond 5000 m were considered ineffective in firefighting. For reclassification of the 'distance from settlement areas' factor, areas that have a distance less than 2000 m from the settlement areas were considered effective in struggling with fire, whereas those with a distance equal to or beyond 2000 m were considered ineffective.

AHP and fuzzy standardization of factors

In order to perform AHP in IDRISI, a fuzzy standardization must be performed for all factors. The factors are rescaled to a particular common range according to some function by fuzzy standardization. In order to use fuzzy factors within MCE, these factors are standardized to the byte level range of 0–255. The suitability increases as the areas get closer to the value of 255; that is, the areas that have same colour with the number 255 are said to be more effective in firefighting than other areas on the same map. It is important to notice that in this study, effective and ineffective areas were determined according to the 'distance from water resources' factor, 'distance from streams' factor and 'distance from settlement areas' factor. The effective and ineffective areas in struggling with forest fire may change when different criteria are considered.

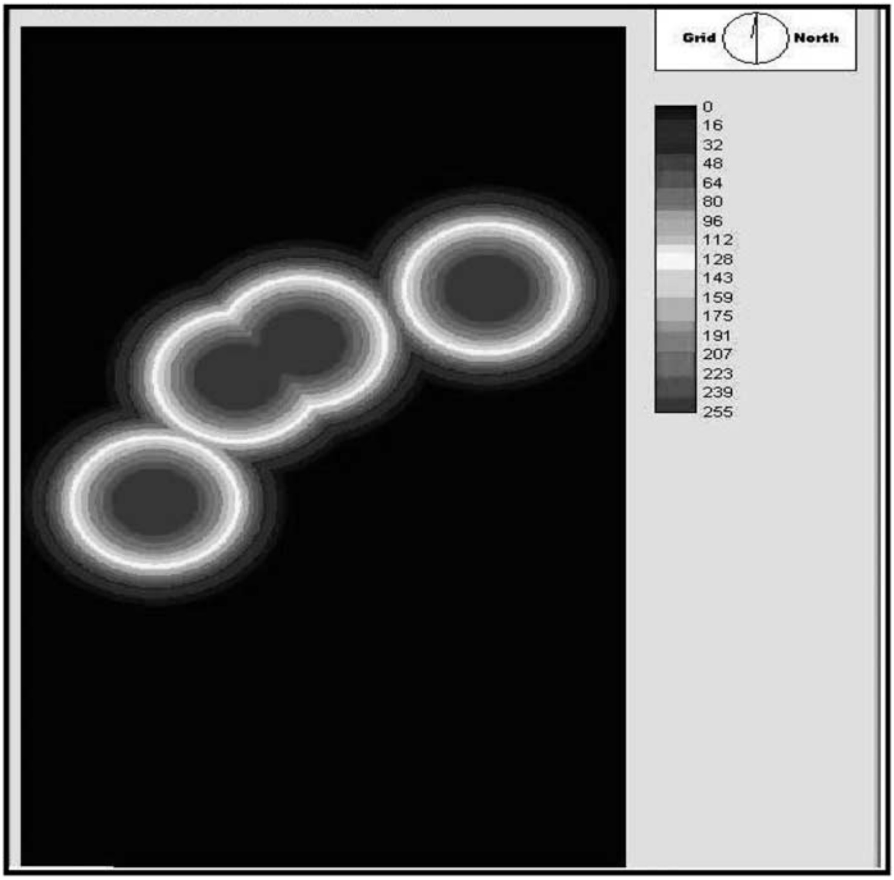

Figure 4: Fuzzy standardized distance map of water resources.

In the fuzzy standardization process, distance maps of the water resources, streams and settlement areas were used.

Figures 4–6 show a fuzzy standardized distance map of the water resources, streams and settlement areas.

Pair-wise comparisons

Following a fuzzy standardization of factors, a pair-wise comparisons matrix was constituted on the basis of the value judgement of staff of the fire-combating department. Figure 7 shows a pair-wise comparisons matrix.

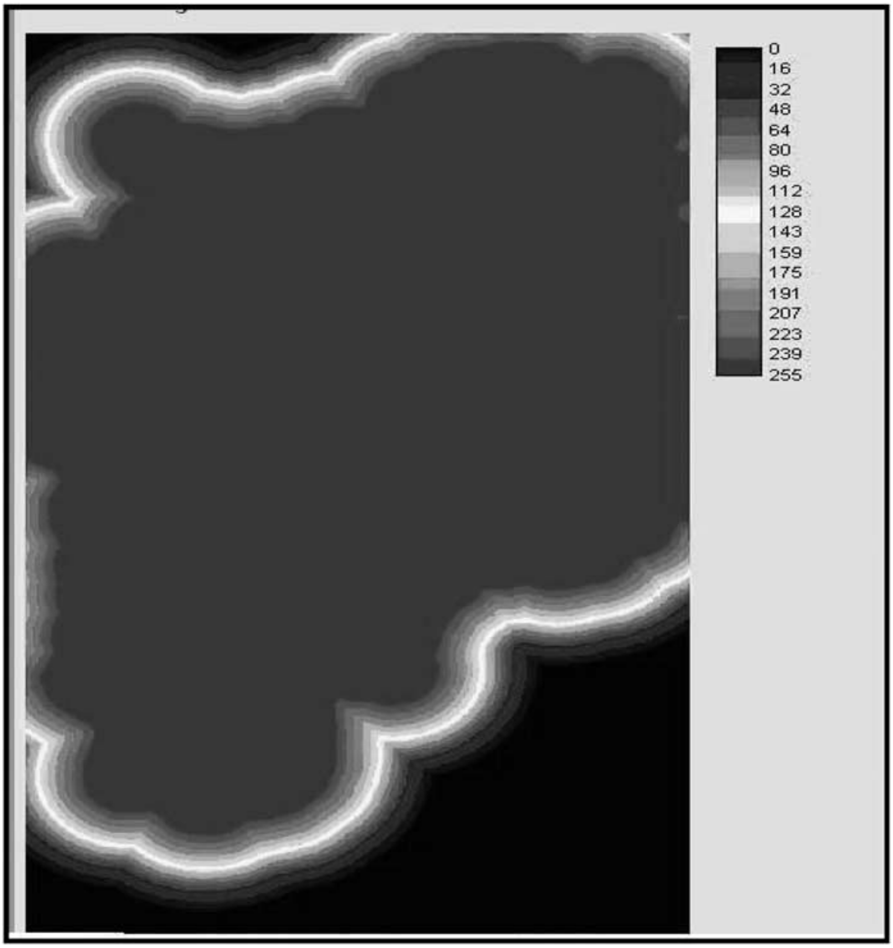

Figure 5: Fuzzy standardized distance map of streams.

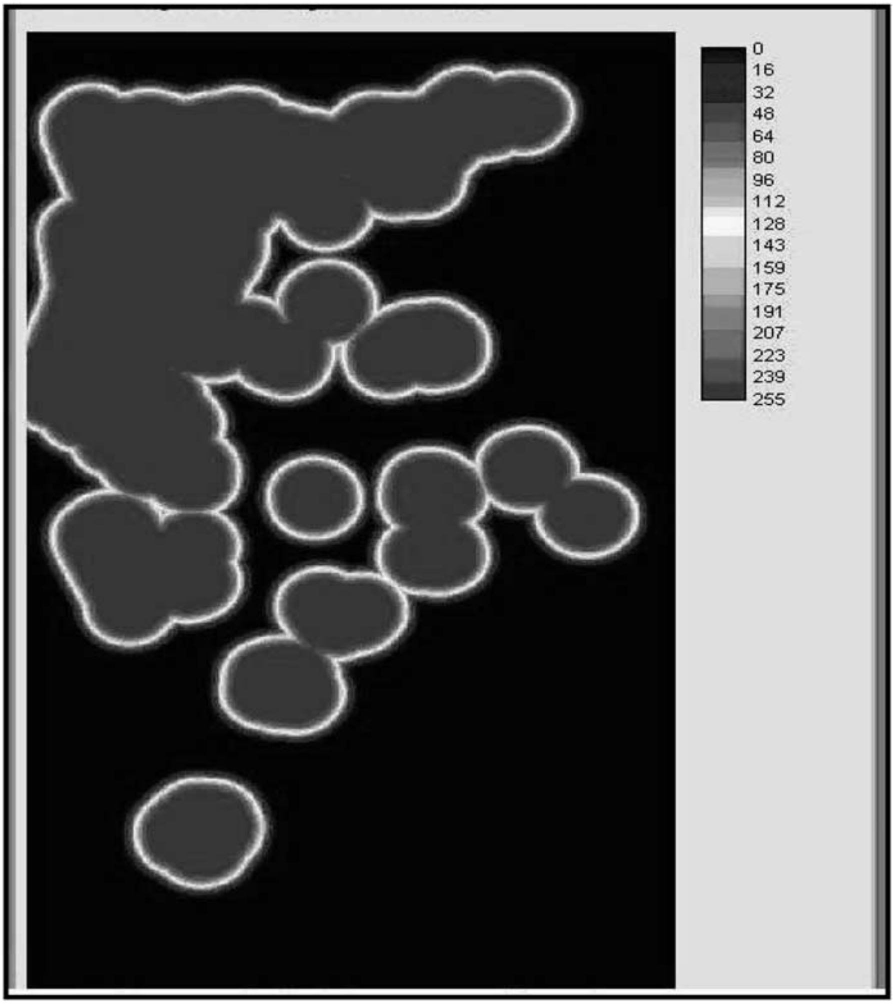

Figure 6: Fuzzy standardized distance map of settlement areas.

Eigenvectors of weights were found as being 0.0877 for water resources, 0.7732 for streams and 0.1391 for settlement areas. These weights show that streams are the most important factor in firefighting planning in this study; that is, the proximity to the streams determines the effectiveness of the study area in firefighting planning. The second important factor in determining the effectiveness of the study area is its proximity to the settlement areas. 'Water resources' is found to be the least important factor in determining the

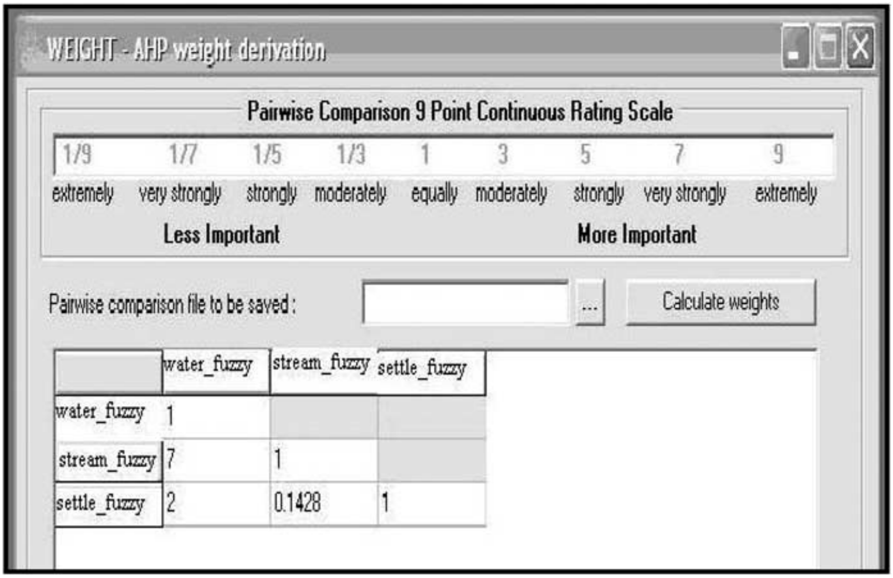

Figure 7: Pair-wise comparisons matrix.

effectiveness of the study area in firefighting planning. The consistency ratio is found to be 0.05 and is acceptable for this study.

All the fuzzy standardized distance maps of the factors were multiplied with their weights by using the image calculator function of the IDRISI software package. Figure 8 represents this multiplication process. In this multiplication process, the fuzzy standardized distance map of water resources was multiplied by 0.0877, the fuzzy standardized distance map of streams was multiplied by 0.7732 and the fuzzy standardized distance map of settlement areas was multiplied by 0.1391, as shown in Figure 8. Figure 9 shows the result of the multiplication process.

A scale of 0–255 appears in the legend of Figure 9. Before the AHP analysis, the three factors used in this study were standardized to the byte level range of 0–255. These factors were thereby standardized to a continuous scale of suitability from 0 (the least suitable) to 255 (the most suitable). Rescaling the factors to a standard continuous scale allows us to compare and combine them. The 0–255 range provides the maximum differentiation possible with the byte data type. In other words, 0 denotes the least effective areas in forest firefighting, whereas 255 indicates the most effective areas in forest firefighting. By looking at Figure 9, the forest manager can visually identify the effective or ineffective areas in coping with forest fires. As a result, forest

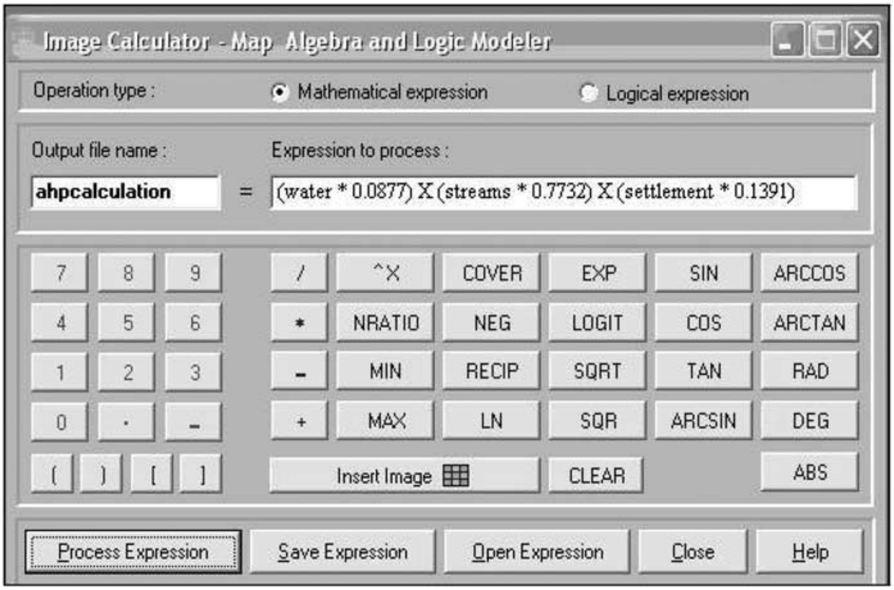

Figure 8: Multiplication of all factors by their fuzzy standardized distance maps.

managers can pay more attention to the ineffective areas and plan firefighting in these areas. In addition, the digital map in Figure 9 is helpful in resource allocation decisions. The positions of ineffective areas can be strengthened by allocating more resources to them.

Figure 10 shows the effective/ineffective areas found in this study.

The marked regions show the intersection of the areas where the conditions of the most streams, the most settlement areas and the most water resources are met simultaneously.

The approach taken in this paper is summarized in Figure 11.

Discussion

Banai (1993) used the AHP available within the IDRISI GIS package, as was done in our study, in order to find optimally suitable sites for landfill. In another study, a GIS-MCDM approach was employed to improve quality of landscape ecological forest planning (Kangas *et al*, 2000). Ananda and Herath (2003) examined the use of AHP in regional forest planning. Jumppanen *et al* (2003) applied GIS-MCDM in a spatial harvest scheduling approach for areas of multiple ownership. Evans *et al* (2004) used Boolean (suitable/unsuitable) and

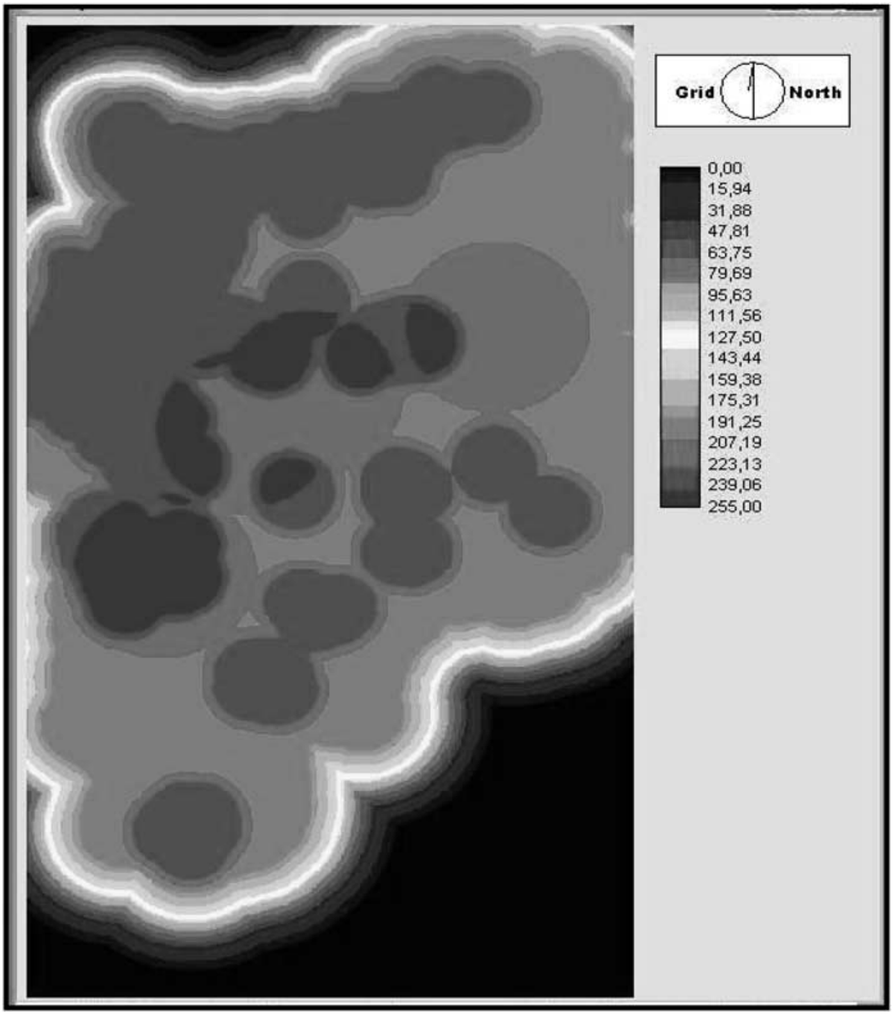

Figure 9: The effective and ineffective areas in coping with forest fires according to AHP.

weighted map overlays in the site search problem for waste management. Mau-Cummins *et al* (2005) used AHP in the selection of forest wilderness sites.

In this paper, an AHP-based approach was taken in determining the effective/ineffective areas to cope with forest fires, according to a predefined set of criteria. In the literature, Boolean analysis has also been used to determine suitable/unsuitable areas for fighting forest fires. However, Boolean analysis is

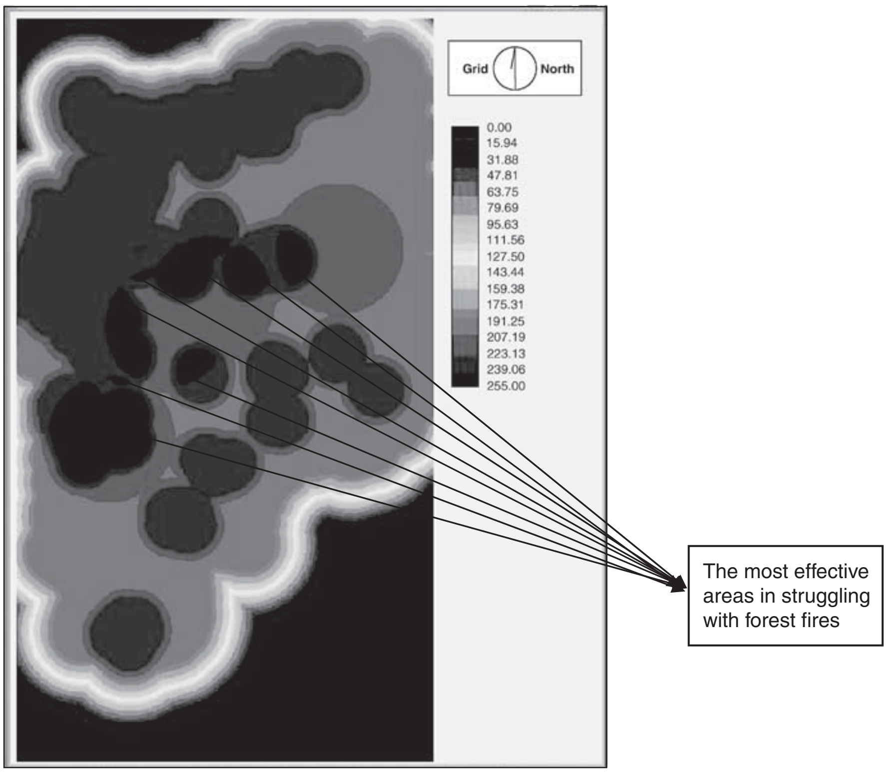

Figure 10: Representation of the most effective areas in a more detailed way.

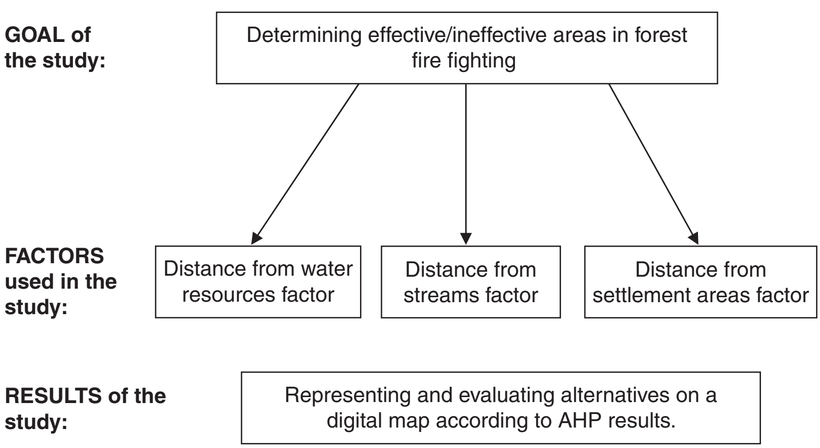

Figure 11: The main steps of the study.

used only when two states are possible (criterion satisfied and criterion not satisfied). Decision-making can be a complex process for many problems wherein Boolean analysis may not work effectively. Furthermore, a Boolean approach requires that all criteria have equal importance when, in some cases, some criteria could be deemed more important than others. In this case, some other techniques, which take into account the value judgement of the decision-maker, such as AHP-GIS integration, must be used.

This study can be further extended by increasing the number of criteria. An important point that must be taken into account is the availability of maps of these additional criteria. The next step of this study is to enlarge the criteria set used in this paper when Izmir Forest Administration Chief Office implements a transition from conventional forest management to contemporary forest management and prepares all digital maps and makes them available to the public usage.

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