GIS Platform for Multicriteria Evaluation of Route Alignments

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(Reviewed by the Highway Division)

Abstract: The selection of an appropriate alignment for a proposed highway is determined largely by relating topographic, urban, and environmental features to geometric design controls. Typically, aerial photographs and topographic, geologic, and soil maps are reviewed. In this paper, a geographic information system (GIS) platform that incorporates the main coverages needed for evaluating route alignments is described. Using the GIS and a geographically referenced database, a decision-aid tool for multicriteria evaluation of route alignments is developed. Possible alignments are evaluated based on community disruption and environmental, geotechnical, and geometric design criteria. The developed decision-aid tool integrates slope stability and roadway design packages and specifically written codes with GIS packages ARC/INFO and ArcView, the latter acting as the system engine and interface. A case study is presented that applies the developed platform to the testing of potential alignments for a proposed 12 km highway to the south of the city of Beirut, Lebanon. Results of the case study demonstrated the advantages of the decision-aid tool and highlighted its potential in providing a quick, multicriteria screening evaluation of possible route alignments.

INTRODUCTION

The task of adopting a particular route alignment for roadways and highways is complex and challenging. Tracing the final alignment for a highway involves making decisions and assessments based on a large set of criteria, some complementary and others competing. Whereas it is possible to determine the most efficient routing based on road geometry (vertical slopes and cut and fill volumes, among other parameters), less objective environmental concerns have become more pressing in the past 15–20 years. Added to the previous list are questions regarding land use, expropriations, societal impacts, and so on. Geotechnical concerns, such as the types of materials cut and the nature of the subgrade soils over which fill embankments are to be constructed, along with potential slopes stability problems, are usually addressed at a later stage, after the preliminary alignment decisions have been made.

Many different types of maps are used at the different phases of the route alignment selection process (political/administrative, land use, topography, etc.). Prior to the past 15 years or so, map presentation and use was a somewhat tedious exercise, which increased in complexity as the number of maps and selection criteria increased.

The introduction of geographic information systems (GIS) has revolutionized the making and, more important, the use of maps. In short, GIS is a set of tools for creating, maintaining, analyzing, and displaying maps and data in digital format. To the civil engineer, this advancement holds great promise as the necessary data and required skills are accumulated (Tonias and Tonias 1995). GIS technology offers the ability to overlay map graphics, merge them with nongraphic data, and perform spatial analyses on various layers of information at any given geographic point. GIS allows the engineer to overlay and analyze spatial data, and to answer questions such as (Star and Estes 1990; Worall 1990), What is at a given location? Where is the location of a certain feature, or associated attribute? What are the identifiable patterns in the features and/or attributes in a geographic area? What happens if something is added or changed in the existing conditions?

Many attempts and applications have been suggested and implemented in the transportation field, mainly in the management of urban transport infrastructure and the assessment of road and traffic impact on the environment. The adaptation of geographic information systems for transportation applications impacts a number of areas, as outlined by Vanderohe et al. (1993). Applications in transportation planning, management, and engineering solicit the available GIS technologies in various ways, as far as required data, analyses, and potential functionality. Examples of typical applications follow. Kastelic and Zura (1992) developed a GIS model for selecting the least risky route in the transportation of hazardous materials. Their model identifies an optimal path based on existing road network geometry and characteristics (road width, radius, and slope), and the class of the hazardous materials to be transported. Zura and Lipur (1995) used GIS spatial analysis to locate the least-impact corridor between origin and destination, based on a minimization of the environmental impact defined in terms of population, fauna, flora, soil, water, air, and climate. Aifandopoulous et al. (1995) developed a tool for travel demand forecasting. They tested different alternative transport infrastructure development schemes, and evaluated their impact on traffic and environmental conditions for the city of Budapest. In the field of real-time transportation management, current GIS systems face some difficult problems associated with handling time-related data. Future advances in this area are sure to expand the use of GIS in the transportation field (Stokes and Marucci 1995; Zhao 1997).

The problem of siting highways and the use of GIS as a decision-aid platform has been addressed by a number of practitioners and researchers; however, the number of criteria and the approaches they have adopted vary widely. For instance, the Illinois Department of Transportation uses GIS to display critical environmental themes relative to the proposed roadway alignments (Hall et al. 1997). Moreover, Bentley and Boggs (1996) implemented a siting study based on two criteria: wetland impacts and right-of-way acquisition costs. GIS databases have also provided the foundation for siting high-speed ground transportation alignments by considering their impact on land

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use and their proximity to urbanized areas (Pritchard 1996). Finally, a combination of GIS tools was used to locate a feasible road corridor through the southern Appalachian Mountains of northern Georgia (Gilbrook 1998). In this application, GIS was used to quantify environmental impacts and engineering considerations for potential corridors.

In the work presented in the current paper, the objective was to construct an integrated tool for the evaluation of potential highway alignments, characterized by the following:

- Automation in proceeding through the various steps
- Reference to a wide set of criteria including pertinent geometric, environmental, and community-related parameters, with special emphasis on geotechnical characterization
- Flexibility in adding/modifying evaluation criteria
- Robustness with respect to various application environments

GIS MODEL AND ROUTE ALIGNMENT DECISION-AID TOOL

The route alignment decision-aid tool within the GIS platform has three main components, which will be described in detail in the sections that follow:

- GIS model—coverages
- Tool engine—analysis procedure
- Evaluation framework

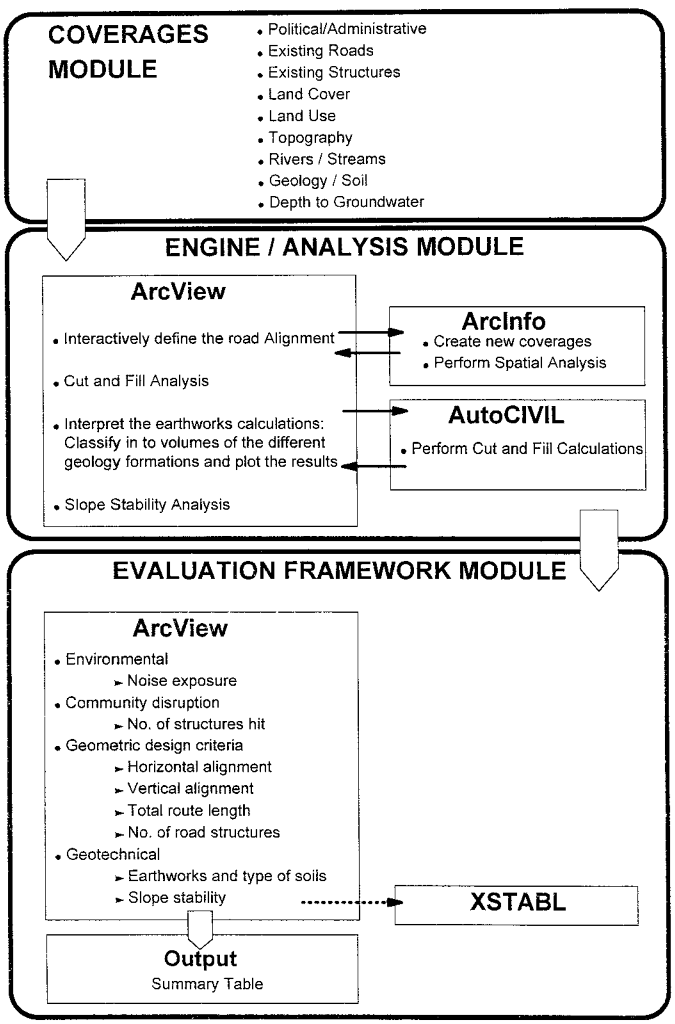

FIG. 1. Simplified Flow Diagram of GIS Decision-Aid Tool

A simplified flow diagram summarizing the various components is shown in Fig. 1.

GIS Model—Coverages

A decision-aid tool for route planners requires a comprehensive body of information. This information should be prepared in digital format, as a base model for the region of interest. The flowchart in Fig. 2 describes the first phase of any GIS project: building the database. The data collection and digitization process is a critical and time-intensive stage. The database requirements are set as one of the objectives of the project at hand. The objectives include a definition of the study area boundary, the required data layers (coverages), the features required in each coverage, the attribute data needed for each feature type, and how to code and organize these attributes. Furthermore, a scale and base map projection are adopted for the whole data set.

It is evident that creating a geographically referenced database for a given region would require different types of data coverages depending on the type of analyses and applications anticipated. The GIS model can be thought of as a geographically referenced base consisting of data layers of various types (graphical features and attributes or associated descriptive properties). The required layers of information are application specific (engineering, agricultural, health science, and so on). The greater the number of data layers, the more complete the model is. However, for the type of application developed in the current project, namely the multicriteria assessment for various route alignments, the following coverages are necessary: political/administrative, existing roads, existing structures, land cover, land use, topography, rivers/streams, geology, soil, and depth to water table.

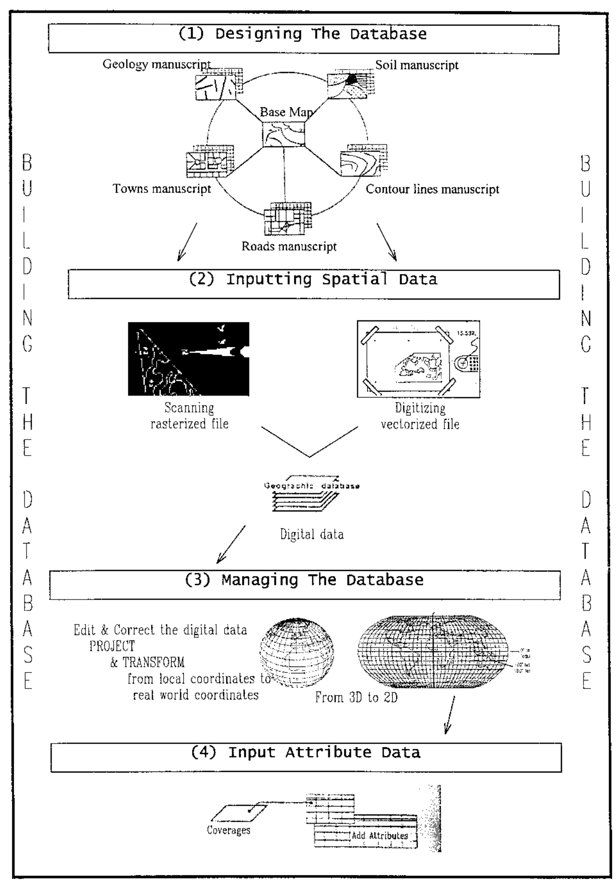

FIG. 2. Building GIS Base Model

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Tool Engine—Analysis Procedure

The database developed using the coverages specified earlier could be used to support a large number of civil engineering applications. The work described in the present paper involves the development of a decision-aid tool within a GIS environment for road designers. It will be referred to as ''tool'' in the remainder of the paper. The tool provides the decision maker with a matrix of various criteria associated with any given alignment of his/her choice. The same approach and base model could be used to develop other potential applications: identifying potential sites for landfills or quarries, mapping areas of high earthquake hazards, and so forth.

The development of the tool was a complex and tedious task, given the variety of assessment criteria sought. The decision-aid tool is built on top of the ArcView GIS package [by the Environmental Systems Research Institute (ESRI)], and it integrates a specialized roadway design package (AutoCIVIL, by Research Engineers). The system engine and the interface environment is ArcView (ESRI). A customized ArcView menu-driven interface was specifically developed by the writers to provide a user-friendly analysis system. The user interfaces with the tool through ArcView using the created pull-down menus. The system itself is a mix of personal computer (PC) ARC/INFO and ArcView scripts (in SML and Avenue languages, by ESRI), computer-aided design (CAD) scripts, and LISP functions.

The resulting tool engine/analysis procedure can be broken down into seven distinct phases/steps (Bedran 1997). The user only needs to define the road alignment on the GIS model of the study area (by defining a series of points, interactively, using the mouse or by assigning particular coordinates). The rest of the analysis is automatically run: The tool developed by the writers will call upon and use the various platforms and developed scripts and computer codes, moving sequentially through all the steps described next without intervention by the user. A final report is generated by the tool itself. Once the alignment has been defined

1. The developed tool engine will identify the successive geology and soil formations underlying the road alignment selected by spatially intersecting the defined road alignment coverage with the geology and soil coverages, respectively (ARC/INFO—automatic).
2. Perform cut and fill analysis using the proper Digital Terrain Model and the pertinent highway section geometry (AutoCIVIL—automatic).
3. Qualitatively interpret the data from AutoCIVIL by classifying the generated cut and fill volumes into the various soil/geology functions. This is achieved by spatially superposing the cut and fill volumes along the road alignment with the underlying soil and geology coverages (ArcView—automatic).
4. Plot the cut and fill diagrams along all cross sections/stations (ArcView—automatic).
5. Identify, evaluate, and highlight potential slope stability problems along the road alignment at both edges of each cross section/station: ArcView scripts perform simple slope stability analyses [infinite slope or Culman-type analyses for finite slopes (Terzaghi and Peck 1967)]. The tool identifies the appropriate case and conducts the appropriate analysis, then reports the factor of safety (*FS*) against slope failure. This analysis is based on spatially combining topology (slopes) and geology/geotechnical data. A complete discussion of the geotechnical details of the slope stability analyses incorporated in this step is available in Bedran (1997).
6. For those stations where the *FS* was identified to be less than or equal to 1.5, the tool engine automatically creates a file for the station and the critical side of the road. The file format was chosen to be compatible with input files for a more ''sophisticated'' slope stability program, so that more detailed analyses could be easily conducted for these stations. XSTABL by Interactive Software was adopted for the input file format. Any other slope stability software input file format can be easily adopted, with minor modifications.
7. Finally, a summary report table is produced.

Evaluation Framework

The evaluation framework is set given the results of the analyses conducted in the step-by-step procedure described earlier. The final report that the engineer can use to evaluate a given alignment includes factual information resulting from the analyses. No assessment as to the relative importance of each evaluation criterion is made, although the writers envisage that such refinements could be incorporated in the future.

Evaluation Criteria

The following is a very brief description of the criteria adopted in the present paper. Three issues should be clarified at this point. First, while the criteria used for evaluation in the current study fall under four categories, namely, geometry, geotechnical, environmental, and community disruption, other categories may easily be added to the evaluation procedure if deemed necessary. Second, the criteria used in each category are prototypical, and more comprehensive criteria, possibly based on more complicated models, may be adopted. In such a case, the GIS platform provides the necessary input data for the evaluation of such criteria, which may require the development of customized modules. Finally, the user is prompted to input reference values for most of the criteria. Values appropriate in certain applications may differ from the ones used in the current case study, and could directly be adopted without the need to modify the evaluation procedure itself.

Environmental Criteria. *Noise Exposure.* In the case study introduced in the present paper, noise exposure due to the presence of the proposed highway is considered to be directly related to the number of structures within a specified distance from the edge of the highway. Other criteria may be developed to relate noise exposure to the traffic volumes, vehicle mix, grades, and pavement characteristics of the proposed highway. These additional characteristics would have to be incorporated in the GIS database.

Moreover, air quality considerations may be incorporated in the environmental evaluation framework by developing models that relate emissions to vehicle speeds, vehicle characteristics, traffic volumes, and other factors, possibly in conjunction with dispersion models. While such models were not included in the prototypical application described later, they may be easily included as additional modules at a later stage.

Community Disruption Criteria. *Number of Structures Hit.* This criterion is defined as the number of structures hit by the highway itself (actual width) plus a user-defined, 10 m band at either side of the edge of the highway. As part of its built-in flexibility, the tool allows for the easy selection by the user of other band widths.

Geometric Evaluation Criteria. *Horizontal Alignment.* The number of horizontal curves with radii less than a certain value is reported, since these curves may constrain the design speed of the proposed highway. In the case of the study discussed later, the reference value is taken to be 200 m, reflecting the minimum acceptable radius for a design speed of 80 km/h.

Vertical Alignment. The tool reports the cumulative length of route segments, with slopes falling in one of three categories associated with no impact, slight impact, and significant

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impact of slopes on passenger vehicle operating speeds, depending on the highway design speed. In the case study, the three categories of slope values for a design speed of 80 km/h were taken to be below 5%, between 5% and 8%, and greater than 8%.

Total Length of Route. Total length of the alignment is calculated and presented in the summary, as part of the evaluation criteria.

Potential Number of Road Structures. During the cut and fill analysis step, critical stations/station clusters, where the cut depth or fill height is greater than 10 m, are identified, and their location and total number reported. The value of 10 m was selected as a point beyond which consideration should be given for possible road structures, which would affect the final cost and desirability of the alignment.

Geotechnical Evaluation Criteria. *Earthworks and Type of Material.* The evaluation criteria reported by the tool are the total cumulative volume of cut, total cumulative volume of fill, and a plot of the cut and fill volumes per geology/soil type. The type of material to be excavated can have a direct impact on the soil associated with the route alternative. Excavation in strong rock versus through relatively soft soils is an example. Furthermore, the knowledge of type of soil over which filling is to be done has significant cost and feasibility implications. Building high fill embankments on clayey subsoils might result in long-term consolidation settlements that are relatively costly to preempt.

Slope Stability. For each cross section/station along the route alignment, a preliminary slope stability evaluation is conducted, as described earlier. The tool reports the number of critical sections/stations as follows:

- Number of sections with factors of safety $FS < 1.0$
- Number of sections with $1.0 < FS < 1.5$
- Number of sections with $FS > 1.5$

This is a very useful, albeit simplified, analysis at this stage.

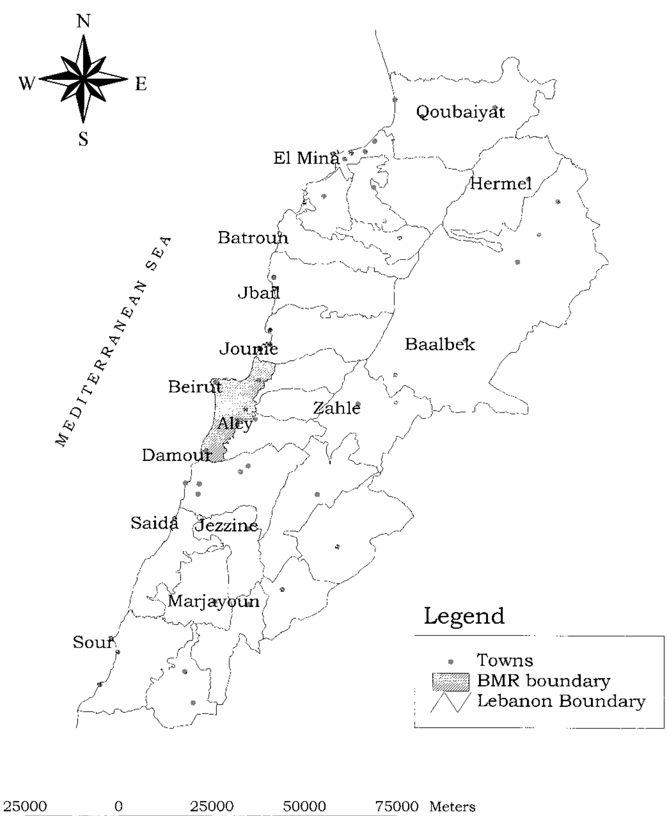

FIG. 3. Map of Lebanon [Study Area (BRM) Is Highlighted]

The cost of stabilization of potentially critical slopes might affect the desirability of particular alignments.

The tool and the GIS model allow for graphical highlighting (on the computer screen and in printouts) of the areas implicated by each of the criteria described previously; e.g., buildings that are within the noise pollution limit are automatically highlighted, stations with problematic slope stability are automatically marked and likewise.

CASE STUDY—BEIRUT METROPOLITAN REGION (BMR)

The approach and tool developed by the writers could be used for any area/region for which the pertinent data are available. The case described next is included to illustrate the use of the multicriteria approach in a real-world application.

Lebanon is emerging from a long and devastating war, and is in the middle of an ambitious and wide-reaching reconstruction and rehabilitation plan. The majority of the projects are concentrated in the BMR, and as such, the BMR was selected as our study area. The BMR is the largest urban center in Lebanon (Fig. 3). It stretches along the coast for approximately 25 km and inland over the adjacent hills and plateaus, bounded by the 400 m elevation contour to the east. The BMR covers an area of approximately 230 km^2. One of the effects of the years of war was the absence of consistent, up-to-date information and hard-copy maps to proper scale, let alone any digital information.

The primary objectives set for the study presented in this case example were as follows:

1. Design and build a geographically referenced model of the BMR, including geotechnical features and characteristics. Building the model involved
   - Assembling the following available coverages for the BMR: roads, rivers, cities, towns, villages, land cover, and land use
   - Building the following coverages from various hard-copy sources: geology, soil, faults, depth to water table, and topography
   - Assigning preliminary geotechnical properties to the different soils and geology formations

     It is important to point out at this stage that building the base model for the BMR was a very time-consuming and challenging task (~12 months). Once the base model has been created, the task of updating the information and developing other applications and uses becomes less problematic.
2. Applying the multicriteria decision-aid tool that was developed, in the selection process, for potential route alignments using the newly created geographically referenced model of the BMR.

TABLE 1. Typical Design Geotechnical Properties Assigned for Different Categories

Soil category (1)	Soil/rock type (2)	$\phi°$ (3)	c (kN/m^2) (4)	γ (kN/m^3) (5)
I	Strong rock	35	500–1,000	22
II	Medium strong rock	30	200–500	20–22
III	Weak rock	25–30	50–200	20
IV	Marl	20	100–300	18–20
V	Weak clayey soils, Sandy clay, Clayey sands	10–25	25–150	17–20
VI	Dense sands	35–40	0	18
VII	Loose sands	25–35	0	16
VIII	Weakly cemented sands	30	30–50	16

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Methodology—Designing and Building GIS Model of BMR

The following coverages were prepared as part of the effort described in the present paper:

Geology and Faults Coverages

The geological map for all of Lebanon was digitized at a scale of 1:200,000. The geology data for the study area were digitized using a more detailed scale of 1:50,000. The associated attributes with the geology and faults coverages include the name of the geologic formations, and their age, type, and origin. The sources of the information included in these coverages are the work of Duberteret (1955) and some more recent observations (evidence of previously unmapped geological structural contacts and faults).

Soil Coverage

The available soil cover maps were digitized and prepared for all of Lebanon (1:200,000). The associated attributes with the soil coverage include the name and general classification of the soil types.

Depth to Water Table Coverage

The depth to water table for the whole BMR was digitized from the scale of 1:20,000, with 10 m contour intervals. The main sources of data for this coverage were a number of studies done in the early 1970s on water wells in the BMR and input from various government agencies. The writers were constrained to the aforementioned sources, given the fact that during the 20 years of strife no data were collected. Nevertheless, recent evidence (new wells and geotechnical soundings) suggests that minor changes have occurred in the past two decades in the level of the water table at the particular locations tested. In any event, as more recent data become available, this coverage could be very easily updated.

Topology Contour Lines Coverage

The scale of 1:20,000 was adopted for digitizing the topology contour lines, resulting in 50 m contour lines. In areas

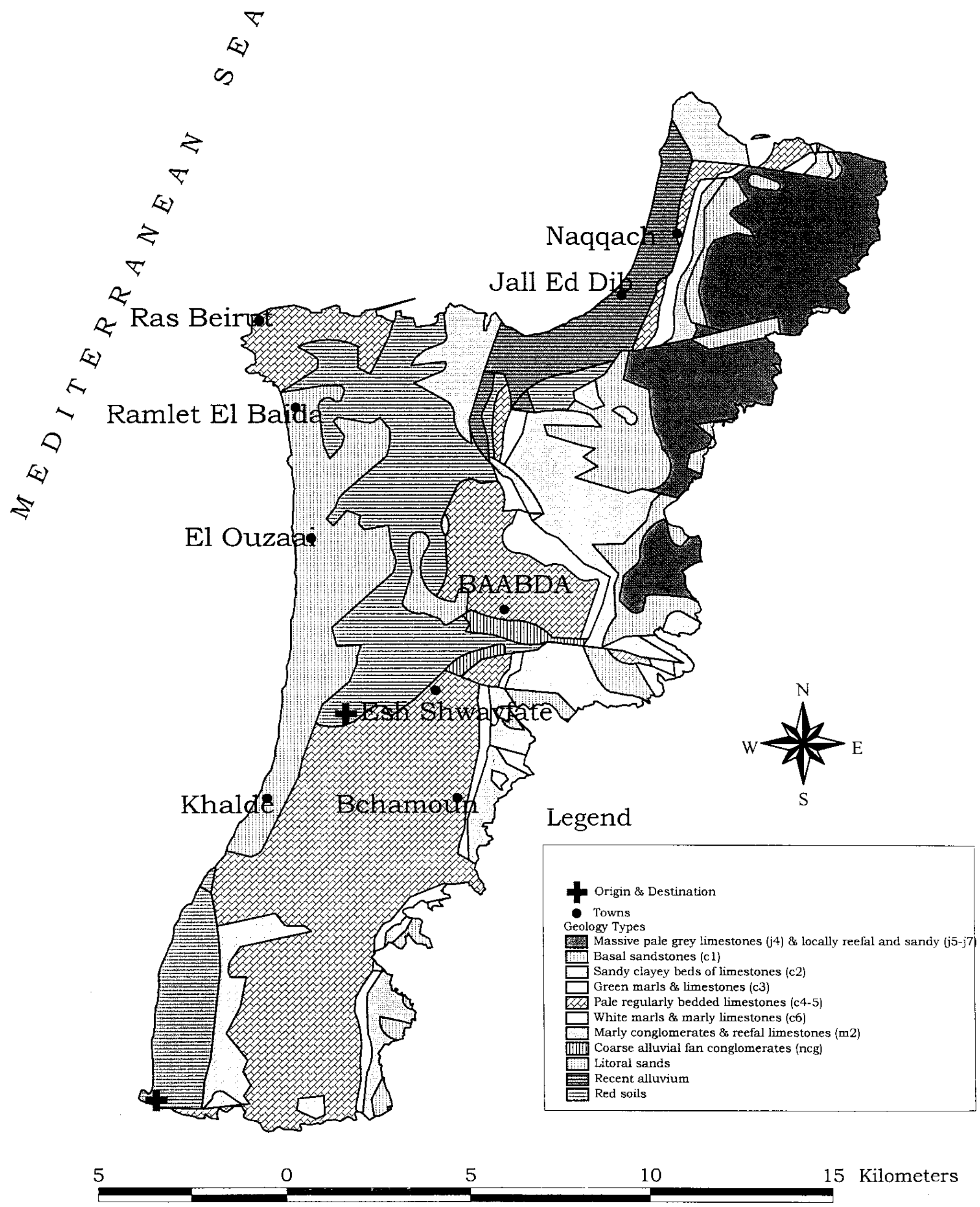

FIG. 4. South Mountain Highway Project: Origin and Destination Points

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where more precise information was available, closer contours were possible (20 m), and they were incorporated in the geographically referenced model of the BMR.

As mentioned earlier, other coverages were already available and were obtained in digital format and incorporated in the BMR model: roads, rivers, cities, towns, villages, and existing structures, land cover, and land use.

Geotechnical Properties Coverage

Given the application and the multicriteria route alignment evaluation tool developed, information regarding the geotechnical properties of the soil and geology formations is needed. The tool conducts rough slope stability evaluation that requires some knowledge of the engineering properties of the various soils/rocks formations. These properties are the bulk unit weight, γ, and parameters describing the shear strength characteristics (cohesion, c, and the angle if internal friction, ϕ). Assigning geotechnical properties, even of a rough and indicative nature, is not a trivial task. A combination of the following sources was relied on in establishing the geotechnical reference properties used in the model of the BMR:

- Engineering geology
- Available data from field and laboratory investigations: results of the subsurface investigation campaign from the past 40 years were queried.
- Previous studies and attempts at qualifying geotechnical properties of certain strata in the BMR (Ghannam 1987)
- Judgment and experience of practicing geotechnical engineers

It is very important to note here that the prior list by no

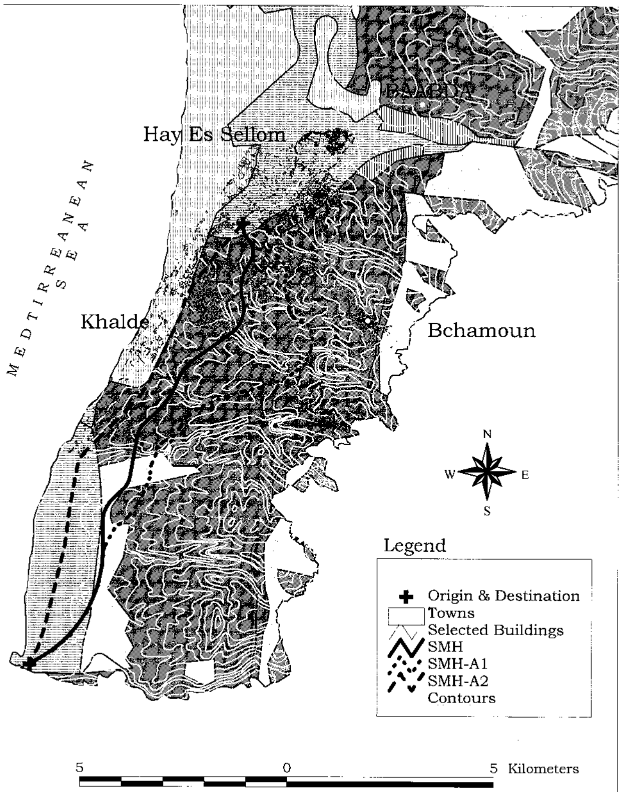

FIG. 5. Alignments SMH, SMH-A1, and SMH-A2

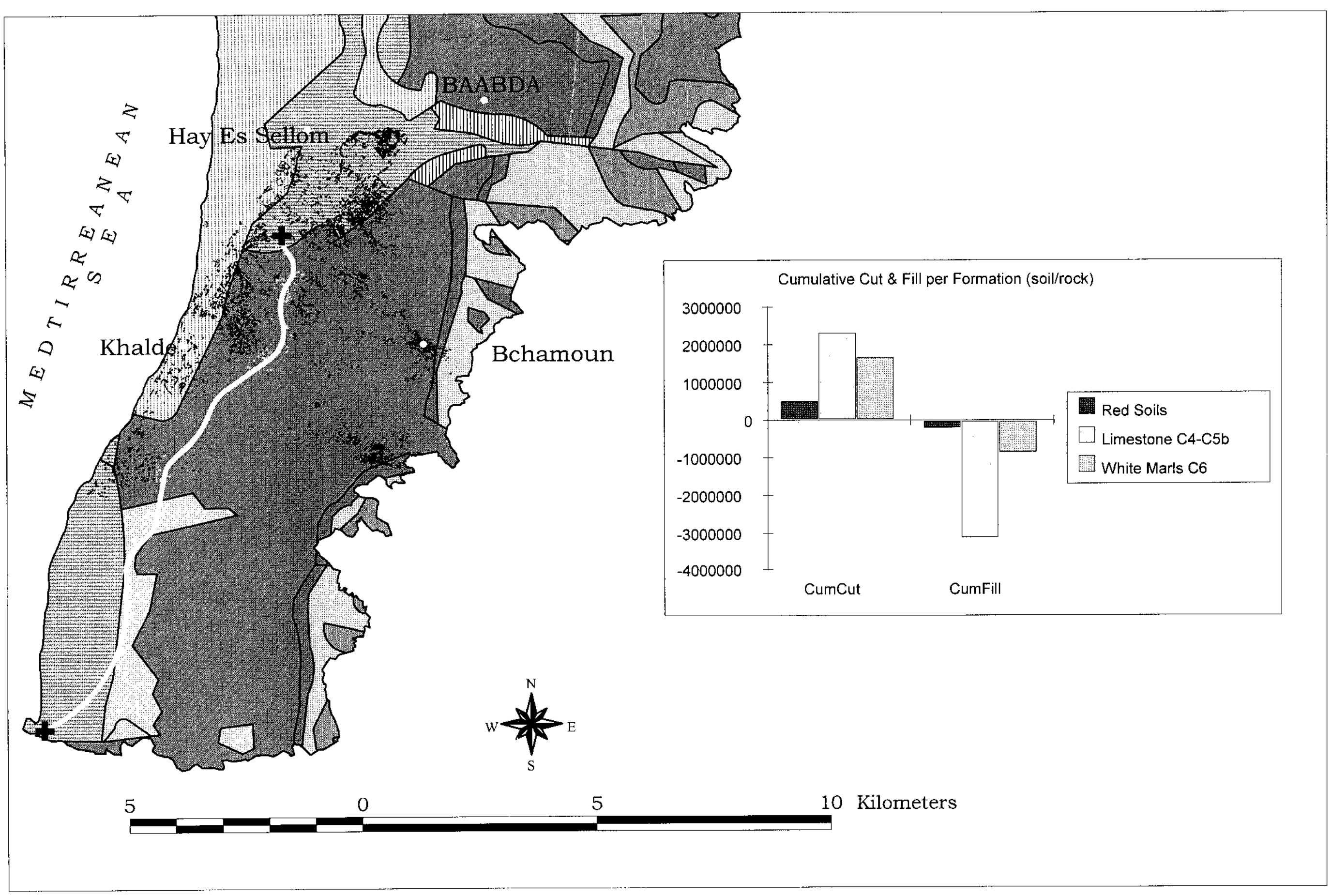

FIG. 6. Typical Summary Results (Cut and Fill for Alignment SMH)

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TABLE 2. Summary of Results of Multicriteria Analysis for Alternatives SMH, SMH-A1, and SMH-A2 of South Mountain Highway Project

Criteria (1)	SMH-A2 (2)	SMH (3)	SMH-A1 (4)
(*a*) Community Disruption			
Number of structures within road width + 10 m	13	12	1
(*b*) Environmental Issues—Noise			
Number of structures within edge of road + 150 m	315	102	65
(*c*) Geometric Design Issues			
Number of horizontal curves with radii <200 m	6	7	7
Cumulative length of route segments	—	—	—
0–5% slope	12,053 m	11,405 m	8,030 m
5–8% slope	0	1,268 m	4,182 m
>8% slope	0	—	1,428 m
Total route length	12,053 m	12,673 m	13,640 m
(*d*) Earthworks/Geotechnical			
Slope stability	—	—	—
Number of sections with FS < 1.0	0	0	8
Number of sections with 1.0 < FS < 1.5	0	0	11
Cut and fill	—	—	—
Cumulative cut volume	3.06×10^6 m^3	4.38×10^6 m^3	6.35×10^6 m^3
Cumulative fill volume	3.82×10^6 m^3	4.05×10^6 m^3	17.19×10^6 m^3
Potential number of road structures	9	9	12

means yields values that could be used for final design purposes. They are, at best, indicative and reference values. Thus, BMR soils were classified into the following categories: strong rock, medium strong rock, weak rock, marl, weak clayey soil (sandy clays and clayey sands), dense sands, loose sands, and ''ramleh'' (weakly cemented sands). They exhibit properties of which the values shown in Table 1 are typical.

Application—Alignment Selection for ''South Mountain Highway'' (SMH) BMR

The SMH is part of the peripheral highway that is planned to connect the towns of Khalde and Damour in the BMR (Fig. 4). The model developed for the BMR, which includes all the coverages described earlier, was used along with the decision-aid tool for route alignment evaluation, to test the capabilities of the tool and its usefulness on a real-life project.

At the beginning of the present study, only the point of origin of the proposed highway and its destination are set (Fig. 4). Three separate possible alignments are analyzed. Given the ease and the flexibility of the GIS platform and the developed tool, many alignments could be tested in a very short time period with minimal effort. The three sample alignments are shown in Fig. 5. The solid line is a base alignment referred to as SMH. The dotted lines represent the ''higher elevation alternative'' SMH-A1, and the second alternative alignment SMH-A2 closer to the more heavily inhabited coastal area, respectively. The three trial alignments were run through using the decision-aid tool, and typical results obtained for the cut and fill criteria are shown in Fig. 6. Table 2 is a summary of the reports for the three alignments based on the multicriteria set. A quick reading of Table 2 shows that the tool captured the essential properties of each of the test cases. The results are consistent. For instance, the higher elevation option SMH-A1 affects a lower number of structures (actually hit structures and structures affected by noise pollution) but involves larger cut and fill volumes, more slope stability concerns, longer cumulative highway lengths with high gradients, the potential need for more road structures, and a longer total route length than either SMH or SMH-A2.

CONCLUSIONS, RECOMMENDATIONS, AND FURTHER RESEARCH

The design, setup, and implementation of a GIS based decision-aid tool for route alignment evaluation for highways were presented in the current paper. The advantages that are presented by such a tool are many: The speed, flexibility, robustness, and potential uses are very clear and promising; however, in order to use the tool, a base geographically referenced model of the area of interest needs to be constructed. As the use of GIS technology finds acceptance, base models including a very wide reaching variety of coverages are constantly being developed and are becoming more readily available for many areas throughout the world. With these base models, and the approach described in the current paper, the task of screening and selecting route alignments prior to final design is rendered more efficient, rapid, accurate, and systematic.

The GIS platform developed is only as good as the data available in the coverages and their attributes. Continuous updating of the information base is a must. For the case of Lebanon, efforts are under way to develop more coverages and to update old information, particularly information relating to land cover, existing structure, geotechnical parameters, and so on. Finally, based on the developed spatial database, the same tools and methods described in the paper can be used to develop a large number of other possible civil engineering applications, including identifying potential landfill locations and evaluating their environmental and traffic impacts, as well as similar siting tools for potential quarries.

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