FLOOD MANAGEMENT DECISION MAKING USING SPATIAL COMPROMISE PROGRAMMING WITH REMOTE SENSING AND CENSUS BLOCK INFORMATION

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ABSTRACT

Spatial Compromise Programming (SCP) is a recently developed Multi-Criteria Decision making (MCDM) technique. In contrast to other conventional MCDM techniques, SCP has the ability to address spatial distribution of criteria values in the evaluation and ranking of alternatives. Using this technique, a new toolbox has been developed within the framework of widely used GIS software, ArcGIS. This toolbox provides a user friendly interface to build various user-defined criteria, such as loss of life and flood damage, based on two-dimensional (2D) hydrodynamic simulation results, classified Remote Sensing (RS) image layers, and other GIS feature layers. The SCP computations and generation of final distance-metric map are carried out using raster algebra. The capabilities of the SCP toolbox are demonstrated by solving a test case concerning the evaluation and ranking of hypothetical alternatives for 100-year flood control management of a river in southeastern United States. It is found that the SCP toolbox provides a highly versatile environment for spatial multi-criteria comparison of flood mitigation alternatives, and it may facilitate decision making process. The SCP toolbox can be easily modified for use in a large variety of planning and management applications, and multi-criteria decision making in planning sustainable use of water and land resources.

Keywords: Flood Management, Decision Making, Multi-Criteria Decision Making (MCDM), Spatial Compromise Programming (SCP), ArcGIS, Remote Sensing, Census Block.

1. INTRODUCTION

Flooding is a frequently occurring natural hazard, which costs human hardship and economic loss. The adjective natural refers to the role of geophysical processes in triggering floods. The flood hazard, however, depends not only on exposure to flood waters, but also on vulnerabilities that involve consideration of various socio-economic factors such as population at risk, presence and degree of protection offered by flood defense works, early warning systems, etc. The direct losses that occur during and immediately after the flood event are generally the ones that are most widely used for evaluating the hazard level. These direct losses may be intangible (loss of human life) and tangible (property damage). Indirect losses, which may be tangible (disruption of traffic and trade, increased poverty, etc.) or intangible (increased hazard vulnerability, out-migration, etc.), are more difficult to evaluate, and thus are often unjustly neglected.
Flood control management strategies generally consist of a combination of structural and nonstructural measures. Structural measures aim at modifying the flood flow by building engineered structures such as channel modifications, diversions, reservoirs, levees, dikes, etc. whereas nonstructural measures aim at reducing vulnerabilities in flood prone areas by means of land acquisition and voluntary relocation, flood proofing, flood warning systems, public awareness programs, etc. In general, selection of best flood control management strategy from a number of potential alternatives is a complex multi-criteria decision making process (Simonovic, 2002). The first is the determination of potential direct losses and benefits for each flood management alternative from numerical simulations and/or past flood events. Multiple evaluation criteria are then constructed based on this information. The selection and ranking of alternatives on the basis of these criteria, however, involve various difficulties. One difficulty comes from the fact that stakeholders may have conflicting interests and may differ in opinion concerning the weight to be attributed to each criterion. The spatial variability of decision criteria is another source of difficulty.

Spatial Compromise Programming (SCP), a recently developed mathematical programming technique for Multi Criteria Decision-Making (MCDM), proposes to take into account both the spatial variability and stakeholders’ preferences in evaluating and ranking alternatives. It, therefore, constitutes a promising tool for MCDM for flood control management.

The present paper describes the development of a SCP toolbox within the framework of popular GIS software, ArcGIS. The toolbox provides a user friendly interface for constructing various decision criteria based on the results of two-dimensional flood simulations. Notably the loss of life and flood damage criteria can be constructed by combining numerical simulation results with GIS feature layers, such as census block layer and remote sensing image. The toolbox takes advantage of the fast raster computation implemented in ArcGIS to carry out various calculations needed by the SCP, and displays the final results in the form of maps and statistical analysis charts as an aid in better decision making.

The evaluation and ranking of flood management strategies for 100-year flood of a river in southeastern United States is used to illustrate the capabilities of the toolbox. Designed as a general purpose tool, the toolbox can be easily modified and adapted for solving a large class of multi-criteria decision making applications related to planning and management of water and land resources.

2. MULTI-CRITERIA DECISION MAKING AND SPATIAL COMPROMISE PROGRAMMING

According to Korhonen (1998), a general definition of MCDM refers to “the solving of decision and planning problems involving multiple (generally conflicting) criteria”. “Solving” means that a decision maker will select one "reasonable" alternative from a set of available ones. Tkach and Simonovic (1997) classify MCDM techniques in three groups: (1) outranking techniques; (2) multi-attribute utility techniques; and (3) mathematical programming techniques. The first two techniques can not address spatial variability of the decision criteria values. Either an average or total impact across the entire region of interest is used for evaluation. A flood management strategy chosen based on these average or total impact criteria values for an entire region may produce extremely negative consequences at certain locations, which may not be at all acceptable to all or some of the stakeholders.

In contrast to other conventional MCDM techniques, Spatial Compromise Programming (SCP), one of the mathematical programming techniques, takes into account of the spatial variability of criteria as well as decision makers’ (or stakeholders’) preferences. Tkach and Simonovic (1997) have shown that SCP can be efficiently applied to evaluate and rank the potential flood management alternatives. The SCP method is based on the notion of a distance
metric, which measures how close an alternative is to the ideal solution at each computational cell (raster cell) in the domain of interest. The expression for distance metric is given by:

\[
L_{j,x,y} = \left[ \sum_{i=1}^{n} w_i p \left( \frac{f_{i,j,x,y}^+ - f_{i,j,x,y}^-}{f_{i,x,y}^+ - f_{i,x,y}^-} \right)^p \right]^{1/p}
\]

(1)

where \(i = 1, \ldots, n\) criteria; \(j = 1, \ldots, m\) alternatives; \(x = 1, \ldots, a\) rows in the image; \(y = 1, \ldots, b\) columns in the image. For each cell location \((x, y)\): \(L_{j,x,y}\) is the distance metric value; \(f_{i,j,x,y}^+ / f_{i,j,x,y}^-\) is the best/worst value of the \(i_{th}\) criterion; \(f_{i,j,x,y}\) is the value of the \(i_{th}\) criterion for alternative \(j\). \(w_i\) are weights indicating decision maker preferences; \(p\) is a parameter \((1 \leq p \leq \infty)\) for adjusting the importance of the maximal deviation from the ideal point. According to the above equation, the smaller the distance metric value, the better the corresponding alternative. The graphical illustration of Eq (1) with 6 alternatives \((A_1 \sim A_6)\) and 2 criteria \((C_1\) and \(C_2)\) is shown as in Fig 1.

Distance metric computations can be conveniently performed in a Geographic Information System (GIS) environment (Pereira and Duckstein, 1993) provided that criteria values are prepared in raster image format. Preparation of raster images for various criteria to be included in the analysis are carried out in ArcGIS by combining simulation results with various GIS feature layers and other information. Once the criteria raster images are ready, the calculation of Eq (1) is performed, using raster calculator function, to obtain distance metric images for each alternative. The implementation of this methodology within the framework of widely used GIS software ArcGIS is presented in the following sections.

### 3. DEVELOPING MULTIPLE FLOOD MANAGEMENT DECISION MAKING CRITERIA

In the current practice of flood control management studies, the hydrodynamic computations of the flood are almost always carried out using steady one-dimensional (1D) numerical models. This is often justified based on the difficulty of preparing data for 2D models and long computational times. While it may be acceptable for narrow valleys, in flat areas 1D approach may lead to considerable errors in computed water depths, velocities, and arrival times. The information about flood receding time and flood duration cannot be obtained from a 1D simulation either. The advances in robust, fast numerical schemes, and recent developments in GIS and remote sensing technologies, which facilitate data preparation, make it feasible to use 2D hydrodynamic computations for flood simulations.

In the present study, the flood simulation was performed using CCHE2D-FLOOD (Ying et al., 2003, and Ying and Wang, 2004), which is a fast, 2D finite-volume, shock capturing hydrodynamic model. This model can directly use a raster Digital Elevation Model (DEM) imported from a GIS platform as computational mesh, and produces 4 sets of results: (1) Flood depth, \(h\) (in meters), (2) Flood arrival time, \(AT\) (in minutes); (3) Flood duration (in minutes); (4) Magnitude of flood velocity vector, \(U\) (in m/s). Typically the flood damage computations are based on either maximum flood depth, \(h_{\text{max}}\), or the maximum flow power \((Uh)_{\text{max}}\). Using the toolbox developed in this study, the raster images of various useful criteria can be readily prepared for use in the SCP analysis. Two special criteria used in the present study are: (1) loss of life, i.e. the number of fatalities; and (2) property damage, i.e. estimated economic loss in dollars that would result from the flood event. These criteria are computed based on the simulation results given by CCHE2D-FLOOD, GIS feature layers, and stage-percent damage relationships for various land-use types.
3.1. LOSS OF LIFE ESTIMATION WITH CENSUS BLOCK BOUNDARY

According to Graham (1999), loss of life resulting from flooding is highly influenced by 3 factors: 1) The number of people occupying the floodplain, which is also called people at risk (PAR); 2) The warning time available to the people exposed to dangerous flooding and 3) The severity level of the flooding. In the current practice loss-of-life evaluation is generally computed based on 1D flood simulation results (Dise 2002). Usually, the floodplain is divided into several reaches, and unique values of PAR, warning time and severity are assigned to each reach. The standard procedure also recognizes the use of Monte Carlo simulation for taking into account the uncertainties in various parameters entering into the consideration.

In the present study, since the spatial variation of flood characteristics (depth, velocity, time of arrival, flood duration, etc) are obtained by 2D flood simulation results, one can adopt a new approach to the determination of PAR values based on the census block data, which is usually a GIS vector polygon layer (for example, in TIGER format) showing spatial variation of population. Census blocks are areas bounded on all sides by visible features, such as streets, roads, streams, and railroad tracks, and by invisible boundaries, such as city, town and county limits, property lines, and short, imaginary extensions of streets and roads. After importing census block layer into ArcGIS, the population densities are calculated based on the total population of each census block and its area. Then this feature polygon layer is converted to a raster layer which has the same cell size as in the flood computation results. The cell value, which represents the PAR living and working inside each cell, is reclassified according to the product of population density and the cell area. These operations yield a raster layer showing the PAR distribution.

The warning time is measured as the length of time from issuing of the first public warning until the flood wave reaches the first person of the PAR (Aboelata et. al 2002). In a 2D raster layer format, warning time $W_{issue}$ for each cell location $(x, y)$ can be expressed as:

$$W_{t,x,y} = AT_{x,y} - W_{issue}$$

where $AT_{x,y}$ is the flood wave arrival time; $W_{issue}$ is the time when the first public warning is issued. Since the flood event is assumed to occur at time “0”, $W_{issue}$ can be either positive, or negative, indicating that the public warning is given after or before the beginning of the flood event, respectively.

Finally the flood severity is classified by Graham (1999) as low, medium, and high directly based on the flood depth. In the present 2D approach actual depth values in each cell is used to define local flood severity.

These three factors can be used to compute loss of life for each raster cell and, thereby to calculate a raster criterion map. Fig. 2 shows the dialog box to set up the computation of loss-of-life raster layer. The user is prompted to specify various parameters entering into the computation as well as the weights, $w_i$, to be attached to the loss-of-life criterion during distance metric computations. Based on the parameters supplied by the user, the loss of life in each cell is estimated using the empirical fatality rate values in the Fatality Rate table, which is shown in Fig. 3. In the dialog boxes shown in Figs 2 and 3, the most commonly used default values are already entered. However, the user has the possibility to change these values according to the specific information available. By clicking OK in the dialog box in Fig. 2, the loss of life calculation is triggered using a VBA script (Zeiler, 2001). The final loss of life raster to be used in SCP analysis is obtained by summing up all sub-category layers.

3.2. FLOOD DAMAGE CALCULATION WITH REMOTE SENSING IMAGE

Remote sensing (RS) is a recently developed technology for obtaining information about an area through the analysis of data acquired by a device that is not in contact with the area under
investigation (Lillesand, 1999). The satellite images at different wavelengths can provide important information by showing various urban land cover features, such as vegetation, residential area, or water bodies. Since different land feature types have their inherent spectral reflectance and emissance properties, the RS image is usually classified so that all pixels in the image fall into certain land cover classes or themes. Each land feature has a unique DN (Digital Number) value. By overlaying this classified RS image with the raster layers of flood simulation results, the flood damage calculation can be carried out using arithmetic and relational raster map algebra. The final flood damage image, which shows the spatial variation of damage in dollars, is obtained by combining flood damage layers for all land use types.

The flood damage level for a given type of land use is a function of the flood characteristics such as flow depth, flood duration, etc. Functional relationships for different land use types are generally obtained by field surveys and expert panel investigations. These relationships are presented in the form of stage-percent damage curves.

### 3.3. BUILDING OTHER CRITERIA FROM COMPUTATIONAL RESULTS

In addition to the loss of life estimation and flood damage calculation, the user can also build other types of criteria to be used in evaluating and ranking alternatives using SCP. These criteria can be a linear or nonlinear combination of the computational results. For example, the user can set up a criterion called “Flood Power” by defining it as the product of “Flood Depth” layer and “Flood Velocity” layer. Similarly, criteria like the flood drag force or shear stress can also be built from the computational results. A user friendly interface assists the user in building various criteria conveniently. After setting up the appropriate expression, the computation of the criteria raster layer is accomplished by a VBA script (Zeiler, 2001).

### 4. IMPLEMENTATION OF SCP IN ARCGIS FRAMEWORK

The structural flowchart for the SCP toolbox implemented in GIS environment is shown in Fig. 4. The flood simulations with CCHE2D-FLOOD are carried out for each alternative, \( j = 1 \ldots m \). The simulation results (flow depth, velocity, arrival time, duration, etc.) in raster format are imported into ArcGIS together with various GIS feature layers (eg. census block), remote sensing images (eg. land-use), and other useful information (eg. stage-percent damage curves). Using these information, the user prepares various criteria maps \( (i = 1 \ldots n) \). A dialog box assists the user in this operation. Specialized dialog boxes are also available for easily preparing certain standard criteria such as loss of life (see Figs 2 and 3), and flood damage. Once the criteria layers are prepared, best and worst value raster layers are generated by the toolbox based on the information given by the user regarding the definitions of best and worst values for each criterion (maximum or minimum values).

Given \( m \) alternatives and \( n \) criteria, at this point the total number of raster layers to be processed by SCP analysis is \( m \times n + 2n \). The raster calculation is used to compute distance metric values as defined by Eq. (1). The set of weights \( w_i \) and the parameter \( p \) needed to apply Eq. (1) are specified by the user. This operation produces a separate raster map of distance metric values for each alternative. Based on Eq. 1, the best alternative for a given cell is the one which yields minimum distance metric value. The final SCP map is produced by coloring each cell with the representative color of the alternative, which has the smallest distance metric value. The cells for which all alternatives give the same distance metric value are defined as the common area and assigned a different color. The final map shows which areas are best mitigated by which alternative, and it is used for ranking of alternatives.

### 5. CASE STUDY OF A FLOODPLAIN ANALYSIS

A hypothetical floodplain management analysis for a river valley in southeastern United States has been chosen to illustrate the capability of the designed SCP toolbox. The river
occupies a total basin area of 13,805 km$^2$. The floodplain near a small city is chosen as the study area. This floodplain has a surface area of about 669 km$^2$, and the population (2000 Census) is about 44,700. Most of this area is covered by forests, and forestry-related activities account for a major part of the basin’s economy. Agriculture is also a significant land use activity supporting a variety of animal operations and commodity production. The rest is occupied by urban and industrial area.

The objective of the floodplain analysis is to select the optimum flood control management strategy for the 100-year flood, having a peak discharge of 4,072 m$^3$/s, from a set of potential alternatives. The three alternatives to be considered are: (1) base case (do nothing scenario); (2) construction of a reservoir upstream of the study reach to reduce the peak flow to 2,500 m$^3$/s; (3) construction of two 10m-high dykes to block the flood entering side valleys with dense urban population. The topography of the study area, the three alternatives and the delineation of the flood area for the alternative 1 computed with CCHE2D-FLOOD are shown in Fig 5a.

The four criteria selected for SCP analysis are summarized in Table 1 together with the attached weights, which represent stakeholders’ preference regarding the relative importance of each criterion in the calculation of the distance metric. The table also summarizes the information used in computing each criterion. The flood duration and flood power criteria are prepared using only the results of simulations with CCHE2D-FLOOD. Preparation of flood damage criteria, however, requires land-use information obtained from the remote sensing image shown in Fig. 5b, and stage-percent damage relationships shown in Fig. 4. Due to lack of information on stage-percent damage relationships for other land-use types, only three types of urban cover are considered: high intensity residential area, low intensity residential area, and commercial/industrial/transportation area. The corresponding maximum damage values in case of total destruction are assumed to be $50,000, $40,000, and $80,000, respectively. It is important to note that the percent damage refers to the percent of the total depreciated replacement cost of the structure that is damaged (US Army Corp of Engineers, 1997). Finally, the loss-of-life criterion raster is computed using the PAR distribution obtained from census raster (Fig. 7), and the flow depths obtained from CCHE2D-FLOOD simulation.

The distance metric computations were carried out using a value of $p = 2$ as recommended in the literature (Simonovic, 1989). The final image identifying the best alternative for each location is shown as in Fig 8. The colors clearly indicate which regions benefit from which alternative. Almost no region will benefit from alternative 1, which is the base case with no flood protection measures. Alternative 2, which is the reduced peak flow scenario, gives better results for inundation areas along the river since it reduces the flood depth, velocity and arrival time significantly. Alternative 3 produces better results for the urban area since the dykes are effective in blocking the flood wave. Based on this analysis, the Alternative 3 will probably be chosen, since it protects the urban area best. This analysis can be repeated with different sets of weight values corresponding to different stakeholder viewpoints.

6. CONCLUSIONS

The selection of best flood management strategy from a set of potential alternatives generally requires a Multi-Criteria Decision Making (MCDM) approach that can take into account the spatial variability of the criteria values, as well as the conflicting preferences of stakeholders. The present study shows that, Spatial Compromise Programming (SCP) analysis based on 2D numerical simulation results, GIS and remote sensing technologies can significantly improve the accuracy of flood hazard assessment, and assist in evaluation and ranking of flood control management strategies for flood control decision making.

A toolbox developed in ArcGIS environment allows the application of SCP analysis based on raster images of user-defined criteria prepared by combining 2D flood simulation results
with various GIS feature layers. This toolbox can be easily adapted for use in a wide range of spatial MCDM applications in water and land resources management. The studies are underway to include risk analyses under uncertainty into standard SCP analysis.

ACKNOWLEDGEMENTS
This work is a result of research sponsored by the USDA Agriculture Research Service under Specific Research Agreement No. 58-6408-2-0062 (monitored by the USDA-ARS National Sedimentation Laboratory) and The University of Mississippi. The authors wish to acknowledge the help of Dr. Dalmo Vieira in GIS programming, and the use the data provided by Georgia GIS Data Clearinghouse (http://gis.state.ga.us/), USGS Daily Water Data for Georgia (http://waterdata.usgs.gov/ga/nwis/dv/), and NOAA Advanced Hydrological Prediction Service (http://weather.gov/rivers_tab.php).

REFERENCES
Fig 1 Graphical illustration of Eq (1) with 6 alternatives and 2 criteria. The figure assumes that the ideal values for both criteria are the maximum values.

Fig. 2 Dialog box for setting up loss of life computations. The user is required to enter various parameters regarding flood severity, warning time and public understanding of flood severity.

Fig. 3 Dialog box for defining the fatality rates based on flood severity, warning time, and public understanding of flood severity (default values taken from Graham, 1999).
Fig 4: Structural flowchart of SCP toolbox in ArcGIS environment.

Fig 5: (a) DEM showing the flood delineation for the base case (do nothing scenario) and the location of the structural measures; (b) LANDSAT 7 remote sensing image.
Table 1 Summary of decision criteria used in SCP analysis of the test case.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight (w)</th>
<th>Flood simulation results from CCHE2D-FLOOD</th>
<th>Remote Sensing Image</th>
<th>Census Block Layer</th>
<th>Stage-Percent Damage Curves</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Depth (h)</td>
<td>Velocity (U)</td>
<td>Arrival Time (AT)</td>
<td>Flood Duration</td>
</tr>
<tr>
<td>Loss of life</td>
<td>0.40</td>
<td>✗</td>
<td>✗</td>
<td></td>
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</tr>
<tr>
<td>Flood Damage</td>
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<tr>
<td>Flood duration</td>
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<td></td>
<td></td>
<td>✗</td>
<td></td>
</tr>
<tr>
<td>Flood Power</td>
<td>0.15</td>
<td>✗</td>
<td>✗</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig 6 Stage-percent damage curves for different land cover (curves fitted to data taken from US Army Corp of Engineers, 1997)

Fig 7 Final census raster layer showing the PAR values used in loss of life computation.

Fig 8 Spatially distributed ranking of alternatives using SCP analysis.