

GIS-Based Spatial Monte Carlo Analysis for Integrated Flood Management with Two Dimensional Flood Simulation

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Received: 13 March 2012 / Accepted: 15 May 2013 /

Published online: 2 July 2013

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Abstract Spatial Monte Carlo Analysis (SMCA) is a newly developed Multi-Criteria Decision Making (MCDM) technique based on Spatial Compromise Programming (SCP) and Monte Carlo Simulation (MCS) technique. In contrast to other conventional MCDM techniques, SMCA has the ability to address uneven spatial distribution of criteria values in the evaluation and ranking of alternatives under various uncertainties. Using this technique, a new flood management tool has been developed within the framework of widely used GIS software ArcGIS. This tool has a user friendly interface which allows construction of user defined criteria, running of SCP computations under uncertain impacting factors and visualization of results. This tool has also the ability to interact with and use of classified Remote Sensing (RS) image layers, and other GIS feature layers like census block boundaries for flood damage calculation and loss of life estimation. The 100-year flood management strategy for Oconee River near the City of Milledgeville, Georgia, USA is chosen as a case study to demonstrate the capabilities of the software. The test result indicates that this new SMCA tool provides a very versatile environment for spatial comparison of various flood mitigation alternatives by taking into account various uncertainties, which will greatly enhance the quality of the decision making process. This tool can also be easily modified and implemented for solving a large variety of problems related to natural resources planning and management.

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Keywords Spatial Monte Carlo Analysis (SMCA) · Flood management · Multi-Criteria Decision Making (MCDM) · Spatial Compromise Programming (SCP) · Remote Sensing · Census block

1 Introduction

River flooding is one of the most common natural hazards in the world, which can cause serious loss in terms of lives, buildings, and infrastructures (Qi et al. 2010). As a consequence, the need for flood risk assessment has become critical (Wang et al. 2011). Flooding is a complex phenomenon which can be affected by changes coupled to terrestrial, socio-economic and climate systems (Kundzewicz et al. 2010). Population-At-Risk (PAR), the degree of awareness of this population, presence and degree of protection measures, existence of early warning systems and the time of release of the warning are all related factors. Under these conditions, flood management strategies such as structural and non-structural flood protection measures can then be treated as a spatial problem (Simonovic 2002; Qi and Altinakar 2011a). Structural measures include dykes, diversion channels, reservoirs, and non-structural measures include flood warning, and mass evacuation, etc. (Yazdi et al. 2012). Representation of these flood mitigation alternatives and objectives in space provides a better insight into the characteristics of the problem and aid decision making.

Conventional flood management decision making tools do not consider the spatial variability of the criteria values, which are used to evaluate potential alternatives. The criteria values, which they use, represent average or total impacts incurred across the entire region being considered. In identifying the best solution from a set of potential flood mitigation alternatives using conventional tools, only the region as a whole is considered. By doing so, the local variation in impacts resulting from the implementation of various flood protection alternatives is ignored. Consequently, the alternative identified as the best for an entire region by a conventional tool is rarely the best for all locations within that region (Simonovic 2002). Spatial Compromise Programming “Simonovic 2009” is cited in text but not given in the reference list. Please provide details in the list or delete the citation from the text.(SCP), one of the mathematical programming techniques of Multi-Criteria Decision Making (MCDM), which takes into account spatial variability of alternatives and decision makers’ preferences, constitutes a promising new tool for flood management decision making (Ernst et al. 2008).

Flood management decision making must take uncertainties into account (Di et al. 2010). The first type of uncertainty arises from the natural variability (inherent randomness) of the variables entering into analysis, and can be spatial or temporal. The second type of uncertainty, the epistemic uncertainty, encompasses the knowledge uncertainty due to lack of sufficient knowledge in modeling the physical processes and the parameters involved, as well as the decision model uncertainty. When the probability distribution functions describing these uncertainties are defined, the Monte Carlo method, based on stochastic sampling, is used to obtain the expected value of flood damage, and its standard deviation. In predicting the consequences of a flood caused by the failure of a control structure, such as a dam break or levee breach, the expected value of loss of life should also be calculated in addition to the expected value of the flood damage (Graham 1999 and Dise 2002).

Developed by National Center for Computational Hydroscience and Engineering, the University of Mississippi, USA, CCHE2D-FLOOD model uses a robust, shock capturing explicit scheme, which allows the presence of mixed flow regimes in the computational domain (e.g. supercritical flows, subcritical flows, transcritical flows, overland flows, and overtopping flows), and can resolve surge-type flow discontinuities. The solution scheme

automatically handles wetting and drying nodes. The 2D CCHE-FLOOD can import GIS topographic data (e.g. USGS DEM, ASCII Raster, regular XYZ format, etc.) to prepare the mesh, and to assign the bed elevations to the nodes. The result file can be imported into a GIS program for post-processing. CCHE2D-FLOOD has been extensively tested against various analytical, experimental and field data. Currently studies are underway for parallelization of the code for faster online simulation.

The main objective of the research described in this paper is to develop a Spatial Monte Carlo Analysis (SMCA) tool in widely used GIS software package ArcGIS version 9.2. Flexible definition of criteria can be realized through the interface of the program from the computational results of a 2D flood analysis model, including linear, nonlinear combinations or even conditional format. Some crucial criteria that are usually implemented for evaluating flood hazard, such as loss of life and flood damage can be constructed within the framework of the tool by interacting with other GIS feature layers like census block layer and remote sensing images like LANDSAT or LiDAR image. The expected results were obtained using the SMCA method, where various uncertainty factors were considered. This tool takes advantage of the fast raster computation in ArcGIS so that various combinations of criteria and alternatives can be evaluated in a short time. The visualization of the results and statistical analysis are also provided to aid better decision making.

A case study of the 100-year flood management strategies on the Oconee River near Milledgeville, Georgia, USA is used to test the capabilities of the program. The computational results from a set of potential flood protection alternatives were evaluated and ranked using the software and the final map clearly shows spatial variability of each alternative. The versatile environment for construction of different criteria and use of other GIS features/raster layers demonstrate that the software can provide the user with a useful tool for flood management decision making. Since the SMCA technique is a general tool developed for evaluation of different alternatives, this tool can be easily modified and implemented to solve a large variety of problems related to natural hazards management.

2 Methodology

2.1 Concepts of Spatial MCDM and Introduction to SMCA Tool

Spatial multicriteria decision problems typically involve a set of geographically-defined alternatives (events) from which a choice of one or more alternatives is made with respect to a given set of evaluation criteria (Jankowski 1995). Spatial multicriteria analysis is vastly different from conventional MCDM techniques due to inclusion of an explicit geographic component. In contrast to conventional MCDM analysis, spatial multicriteria analysis requires information on criterion values and the geographical locations of alternatives in addition to the decision makers' preferences with respect to a set of evaluation criteria. The MCDM component consists of a collection of value or preference structure modeling techniques and associated multicriteria decision models. The value or preference modeling techniques may include criterion weighting techniques as well as the methodology for generating the hierarchical value structure of evaluation criteria (Malczewski 1999). MCDM models implicitly support decision makers in solving semi-structured decision problems. Multicriteria spatial models allow consideration of a number of evaluation criteria (attributes and/or objectives). This implies that usually a multitude of alternative solutions could be recommended for formal analysis by the decision maker. Spatial MCDM approaches allow for flexible integration of the attribute/spatial data and decision maker preferences. Thus the

spatial modeling techniques become more realistic, more flexible, and more acceptable to the user. Spatial MCDM models provide a control mechanism for decision makers, and allow them to introduce qualitative and subjective information during the evaluation and solution processes.

In contrast to other conventional MCDM techniques, such as SCP, one of the mathematical programming techniques, takes into account the spatial variability of alternatives and decision makers' preferences. SCP can be efficiently used to generate, evaluate, and rank a set of potential flood protection alternatives (Tkach 1997). The distance metric values are used to identify solutions that are close to the ideal solution at each location inside the domain of interest. This calculation is performed as in Eq. (1):

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

where $i=1, \dots, n$ criteria; $j=1, \dots, m$ alternatives; $x=1, \dots, a$ rows in the study area; $y=1, \dots, b$ columns in the image. For each cell location (x, y) : $L_{j,x,y}$ is the distance metric value; $f_{i,x,y}^+/f_{i,x,y}^-$ is the best/worst value of the i_{th} criteria; $f_{i,j,x,y}$ is the value of the i_{th} criteria for alternative j . w_i are weights indicating decision maker preferences; p is a parameter ($1 \leq p \leq \infty$). According to the above equation, the smaller the distance metric value, the better the corresponding alternative. Weights w_i are used to reflect the decision maker's preferences concerning the relative importance of each criterion. The parameter p is for adjusting the importance of the maximal deviation from the ideal point. For $p=1$ all deviations are weighted equally; for $p=2$ each deviation is weighted in proportion to its magnitude. For the value $p=\infty$, the min-max criterion is achieved (Simonovic 2002).

A Geographic Information System (GIS) has recently been successfully used for decision making in flood management (Kourgialas and Karatzas 2011). Input data of various criteria from each alternative is done by converting computational results to raster layers within the GIS framework. The calculation of Eq. (1) is performed using a raster calculator function in ArcGISTM software environment and the results are thereby provided by raster images. The advantage of working in a GIS environment is that numerous other GIS feature layers can be brought in as overlays to achieve the loss of life computation and flood damage calculation. The rest of the paper will introduce the methodology in detail and show how to implement SMCA tool within the framework of widely used GIS software ArcGIS.

2.2 Modules of SMCA Tool

2.2.1 Loss of Life Estimation with Census Block Boundary

History shows that floods in a large populated area are capable of causing catastrophic life losses. According to Graham (1999), loss of life resulting from flooding is highly influenced by 3 factors: 1) The number of people occupying the floodplain, also called people at risk (PAR); 2) The amount of warning time that is provided to the people exposed to dangerous flooding and 3) The severity of the flooding. Risk and uncertainty analysis are needed to estimate the fatality rate for different areas of the floodplain.

In order to determine the PAR value, the census block data, which is usually a vector polygon layer (for example, in Topologically Integrated Geographic Encoding and Referencing, or TIGER format) are used in the GIS environment. 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. Generally, these polygons are small in area showing population variation. After importing this layer into ArcGIS, the population density is first calculated by using 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 the flood computation results. The cell value (usually a 30 m by 30 m square in DEM), which represents the number of PAR living and working inside each cell, is reclassified according to the product of population density and the cell area. This operation would obtain a raster layer showing the PAR distribution.

The typical definition of warning time of a flood is the length of time from when the first public warning is issued until the flood wave reaches the first person in the PAR (Aboelata et al. 2002; Poser et al. 2009). In a 2D raster layer format, this definition can be written as in Eq. (2):

$$W_{t,x,y} = AT_{x,y} - W_{issue} \quad (2)$$

In the above equation, for each cell (x, y) of the floodplain, $W_{t,x,y}$ is the warning time and $AT_{x,y}$ is the flood wave arrival time; W_{issue} is the initial time of a public warning. Since the time that the flood event occurs is defined as time "0", W_{issue} can be either positive which means warning is given after the flood happens or negative which means warning is given before the flood happens.

The flood severity definition is usually associated with the flood depth. Low, medium and high severity can be categorized according to Graham (1999). Using the flood severity based method for estimating life loss, the intersection of modified census block information and inundation cell in raster format can produce a map showing the spatial distribution the loss of life information. Raster calculation for the life loss is triggered by using VBA script. For instance, the syntax for retrieving the life loss of a sub category (low, medium and high intensity flood) layer for a medium flood severity with no warning time in the domain is shown as in Eq. (3):

$$[LossLife] = (([D] < H_{high}) \& ([D] \geq H_{low})) \& (([AT] - W_{issue}) < W_{nw}) \times [Cs] \times R_f \quad (3)$$

where $[Lifeloss]$ $[D]$, $[AT]$ and $[Cs]$ represent raster layers of loss of life, flood depth, arrival time and census block information respectively, H_{high}/H_{low} are the limits for high/low severity flood depth, W_{nw} is the time limit for no warning, R_f is the corresponding fatality rate. The total loss of life is estimated by summing the three low medium and high flood severity layers. This raster layer can be used for further SCP criteria evaluation.

2.2.2 Flood Damage Calculation with Remote Sensing Image

Integration of the satellite and GIS datasets are often used to prepare the flood zonation mapping (Patel and Srivastava 2013). The second criterion used in the evaluation of the alternatives is the dollar value of damage to the flooded structures within the region of interest. Field surveys or interviews and expert panel opinions are the two primary sources of the data used to develop depth-damage relationships for structural damage and its content groupings and alternative residence types. Flood depth here refers to the depth of the flooding above or below the first floor of the structure. The percentage damage to the structure refers to the percent of the total depreciated replacement cost of the structure that is damaged (US Army Corps of Engineers 1997). For this research, four different kinds of structures are considered for flood damage calculation, including high density residential area, low density residential area, commercial/industrial/transportation area, and urban/recreational area. The estimated dollar value for the above 4 categories is \$500,000, \$400,000, \$300,000 and \$100,000 respectively on a 30 by 30 m cell basis.

Remote sensing (RS) can provide important information by showing various urban land cover features, like vegetation, residential areas or water bodies (Lillesand 1999). Since different land feature types have their inherent spectral reflectance and emittance properties, the RS image is usually classified so that all the pixels in the image fall into certain land cover classes or themes. Each class of land features manifests a unique digital number (DN) value. By overlaying the classified RS image on flood depth image, the flood damage calculation can be achieved using arithmetic and relational raster map algebra. For example, the following syntax will generate a raster layer showing the flood damage distribution in dollars:

$$[DamageMap] = \sum_{l=1}^L ([LandUse] == DN_l) \times (Eq(Depth-Damage)_l) \times DV_l \quad (4)$$

where $[DamageMap]$ is the raster map showing flood damage in dollars; $[LandUse]$ is the classified land use RS layer for the research area; $l=1, \dots, L$ land use type. For land use type l , DN_l is the digital number; $Eq(Depth-Damage)_l$ is the depth-damage relationship equation, DV_l is the dollar value for a cell. Note that the relational operation $([LandUse]==DN_l)$ will produce an output raster layer with all the cells occupied by land use type l having a value “1” (also means “TRUE”). The final damage image is then obtained by combining all the flood damage layers across all the land use categories. This raster map directly shows the variations of damage in dollar values in space. By overlaying the classified RS image with the flood inundation image, the flood damage calculation can be achieved in GIS as shown in Fig. 1 (Altinakar et al. 2008).

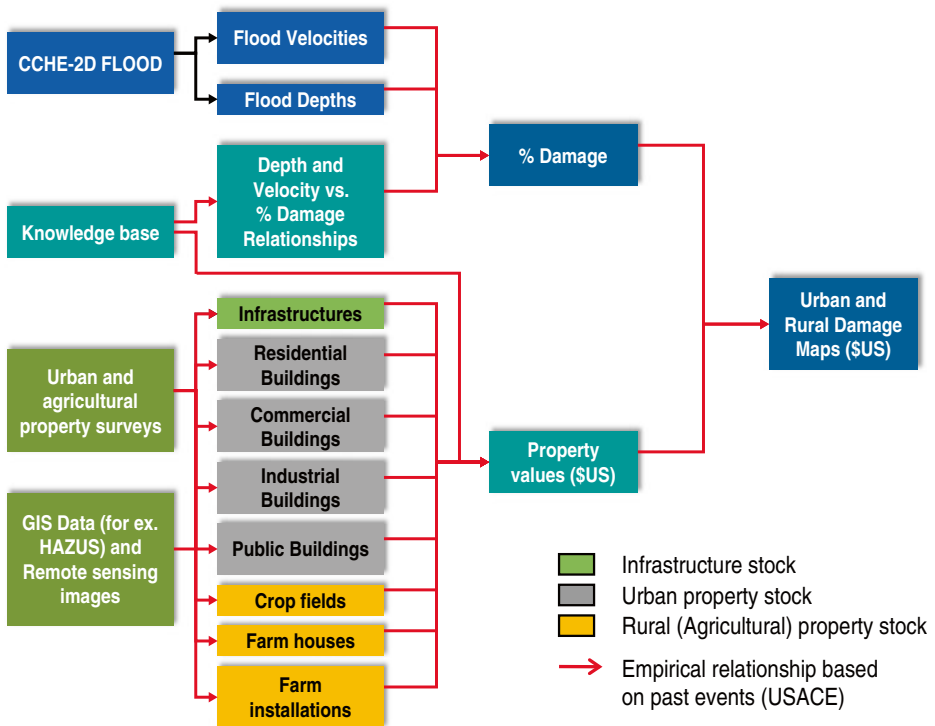


Fig. 1 Urban Flood Damage Calculations with RS Image

2.2.3 Risk and Uncertainty Analysis

Flood hazard management formulated as a spatial decision making problem is subject to multiple sources of uncertainty. A risk analysis approach to flood management uses probabilistic descriptions of the uncertainty in estimates of selected important variables. These enter into the computation as randomly distributed stochastic variables. The date and time of the flood, for example, is a parameter which may significantly affect the PAR distribution. In current practice, an event tree, such as the one given in Fig. 2, can be used to estimate the PAR variation (Dise 2002) with date and time. The time of releasing of the warning with respect to the beginning of the flood event, local flood severity levels and PAR fatality rates also have uncertainties. For flood damage calculation, five important parameters including number of structures, structure value, content value, other value and first floor height, are also treated as randomly distributed variables for each land use category.

For each uncertainty variable, one of the four most commonly used distributions, including normal, logarithms, triangular and uniform distributions (Table 1) is applied and the related parameters are supplied through the user interface with date and time. Based on the results of a 2D hydrodynamics analysis, ArcGIS functions are used to carry out a Monte Carlo analysis by stochastic sampling of the uncertainty variables.

Monte Carlo simulation refers to a mathematical technique that converts uncertainties in input variables of a model into probability distributions (Mooney 1997). By combining the input distributions and randomly selecting values from them, it recalculates the simulated model many times and brings out the probability of the output (Charalambous 2004). In this study, the Monte Carlo simulation approach is first used to draw samples of *n* different uncertainty parameters from their predetermined probability distribution. Then, the flood management tool is used with those samples. The whole procedure is repeated for a large number of model runs and the final results (loss of life and flood damage, with mean, min/max and standard deviations) are then calculated from the results. The number of runs required to achieve convergence can either be determined by using Kolmogorov-Smirnov and Renyi statistics, or, more arbitrarily, by experience (Beck 1987). Theoretically, the greater the number of simulations, the better resemblance between generated and parent distribution of each random variable. However, for the complex flood management decision support system with many uncertainty parameters running on a GIS platform, the computational time to achieve convergence may become prohibitively high. Therefore, there is often a trade-off between desired accuracy and affordable computational expense. Generally, Monte Carlo runs should be greater than 5,000 times.

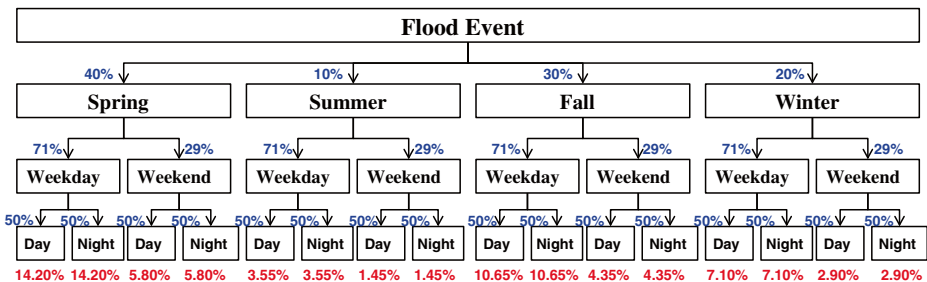
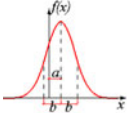
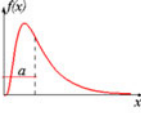
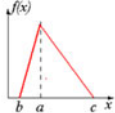
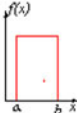


Fig. 2 Event tree for the breakdown of a year into to time periods when PAR is different. Blue numbers indicate the probability of branches and the red numbers correspond to the final probabilities at the terminal nodes.

Table 1 Characteristics of normal, lognormal, triangular and uniform distributions used in Monte Carlo analysis

	Normal	Lognormal	Triangular	Uniform
Parameters	$a = \text{mean};$ $b = \text{variance} (b>0)$	$a = \text{median};$ $b > 0$	$a = \text{mode};$ $b = \text{min}; c = \text{max.}$	$a = \text{min};$ $b = \text{max.}$
Probability density function	$f(x) = (\sqrt{2\pi b})^{-1} e^{-\frac{(x-a)^2}{2b}}$	$f(x) = (x\sigma\sqrt{2\pi})^{-1} e^{-\frac{(\log x - \mu)^2}{2\sigma^2}}$ where $\mu = \ln(a)$ and $\sigma^2 = \ln(b)$	$f(x) = \begin{cases} \frac{2(x-b)}{(c-b)(a-b)}, & x \in [b, a] \\ \frac{2(c-x)}{(c-b)(c-a)}, & x \in [a, c] \end{cases}$	$f(x) = \frac{1}{b-a}$
				

It should be noted here that the results of the Monte Carlo simulation show the spatial variances of loss of life and flood damage at each geographical location (based on the resolution of the data, called pixel location) in the research area. Hence, this method is called “Spatial” Monte Carlo simulation method. The final results can be displayed in the form of raster/vector maps as an aid for better decision making related to flood hazard management (Qi and Altinakar 2011b). It can also be used to evaluate the cost effectiveness of alternative approaches to strengthening flood control measures.

2.2.4 GIS Post-Processing

The system structure is shown in Fig. 3. Having decided upon the criteria from the computational results, raster images are generated for each of the criteria with the overlays of other GIS feature layers, in which each raster cell contains the unique criteria values for all distinct geographic locations. Since the best/worst criteria values are also required for computation of the distance metric, in ArcGIS, the “cell statistics” function is used to determine the best/worst

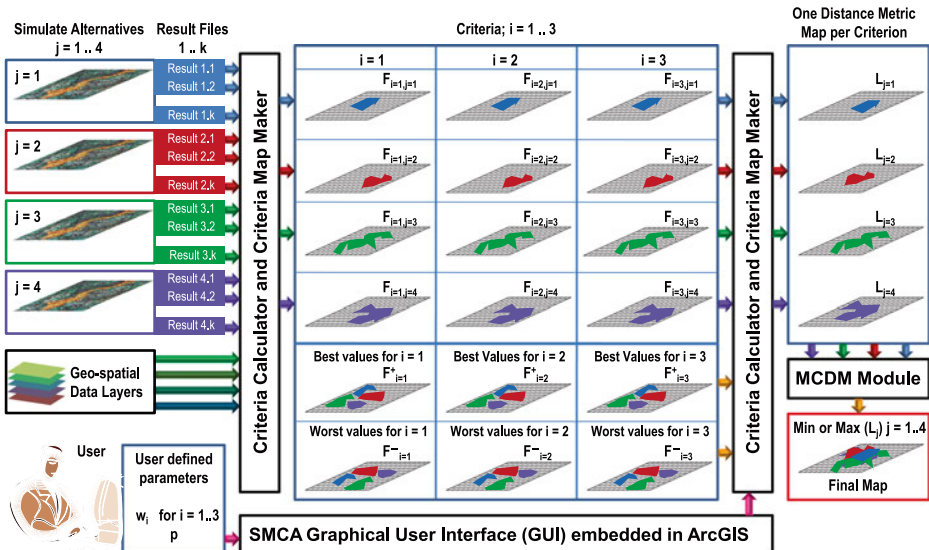


Fig. 3 Flow Chart of SMCA within GIS Framework

value for each location of the criterion. Suppose there are m alternatives and each of them contains n criteria, the total number of maps after this operation is $(m \times n + 2n)$.

After all the required information is obtained, the distance metric value for each alternative is calculated using Eq. (1). This set of distance metric maps is stored in the decision support module. The cell-by-cell comparison of the distances metric maps will produce the final map showing the best alternative for each location within the region of interest. This is achieved by using relational operation in map algebra module in ArcGIS® with the following syntax:

$$[FinalMap] = \sum_{j=1}^m (([DisM_j] < [DisM_k]) \& ([DisM_j] < [DisM_{k+1}]) \cdots \& ([DisM_j] < [DisM_m])) \times j$$

$$k = 1, 2, \dots, m \text{ and } k \neq j$$
(5)

where $[FinalMap]$ is the final raster layer showing the best alternative for each location; $j, k=1, \dots, m$ alternatives; $[DisM_j]$ and $[DisM_k]$ are the distance metric maps of alternative j and k . By using this equation, the result map identifying the smallest distance metric for each location is obtained, with each cell containing a number corresponding to the best alternatives' index.

3 Demonstration of SMCA and Case Study Application

A floodplain analysis of Oconee River near Milledgeville, Georgia of the United States has been chosen to test the capability of the designed SMCA tool (Fig. 4). The Oconee River extends from central northern Georgia, northeast of Atlanta, to central southern Georgia, occupying a basin area of 13,840 km² (Oconee River Basin Management Plan 1998). The Oconee River basin contains parts of the Piedmont and Coastal Plain physiographic provinces, which extend throughout the southeastern United States. The floodplain of Oconee River near the City of Milledgeville has an area about 669 km², 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 area.

The main objective of the floodplain analysis is to identify the best flood mitigation strategy from a set of potential alternatives. A 100-year flood computed by USGS regression equation is assumed to occur in this area. To alleviate the flood hazard, the following flood protection strategies are considered to be the alternatives: (a) construction of a reservoir upstream of the river to reduce the peak flow to 2,500 m³/s (Test study shows that 2,500 m³/s will not cause inundation to the major roadway and buildings inside the city limits); (b) construction of 10-m dykes around specific areas to block the flood. In order to compare the results, another alternative which is called base case is also simulated without any flood protection measures. The locations of these alternatives are shown in Fig. 5.

Among the various output produced by the simulation of the flood, two datasets are particularly important for carrying out a consequence analysis. One of these datasets contains the maximum flow depths over the computational domain and the other arrival time of the flood. These two files were imported into the system implemented in ArcGIS as raster layers. These raster layers were then interfaced with the PAR data layer and the classified land-use layer to estimate potential loss of life and urban and agricultural damage. The principles of these analyses were already explained in section 2.1 and 2.2. The percent

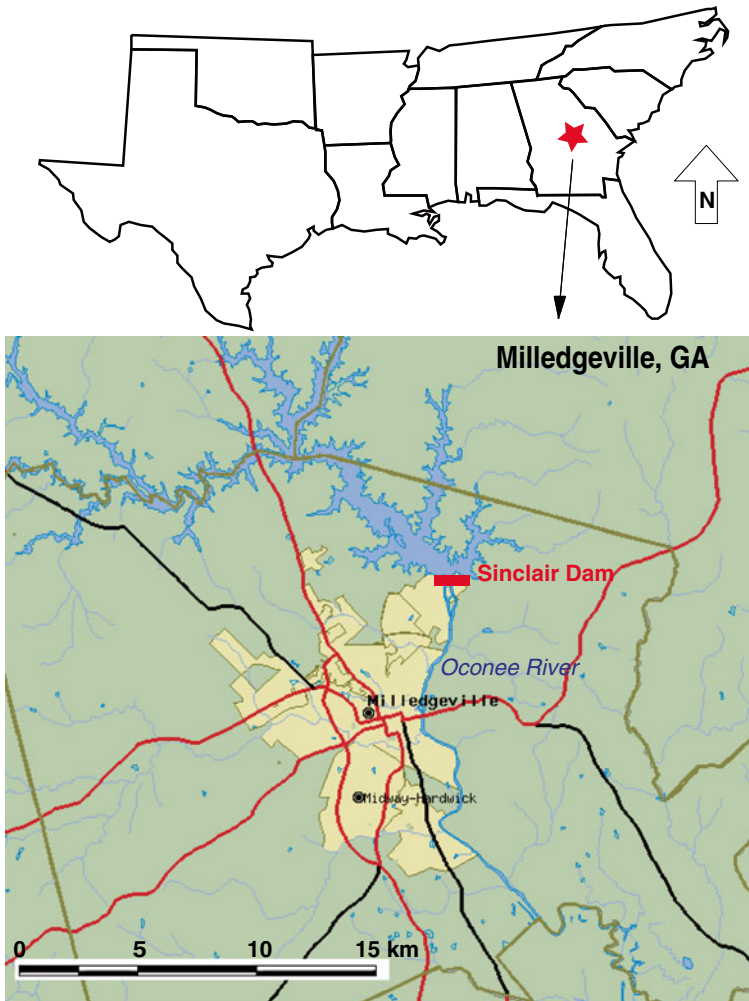


Fig. 4 Study Area: Milledgeville, Georgia in Southeastern United States

damage versus stage curves used for different urban land use types listed in Table 3 are plotted in separated figures. These curves were obtained by fitting a polynomial to the original data by the US Army Corps of Engineers (1997). The input data used for the spatial Monte Carlo Analysis of loss of life and flood damage for both urban and rural areas are presented in Tables 2 and 3.

For this study, four different types of flood water impacts are used as criteria to evaluate the proposed alternatives using the SMCA toolbox. The criteria, weights (obtained from the survey questionnaires from the stakeholders) and the associated computational results from CCHE2D-FLOOD (results from other model like Mike-11, Flo-2D, TUFLOW, RMA4 and etc. can also be used for SMCA tool.) are listed (selected option is indicated by “X”) in Table 4. The unique value of $p=2$ is used here as recommendations from the literature (Simonovic 2002) with sensitivity analysis tests.

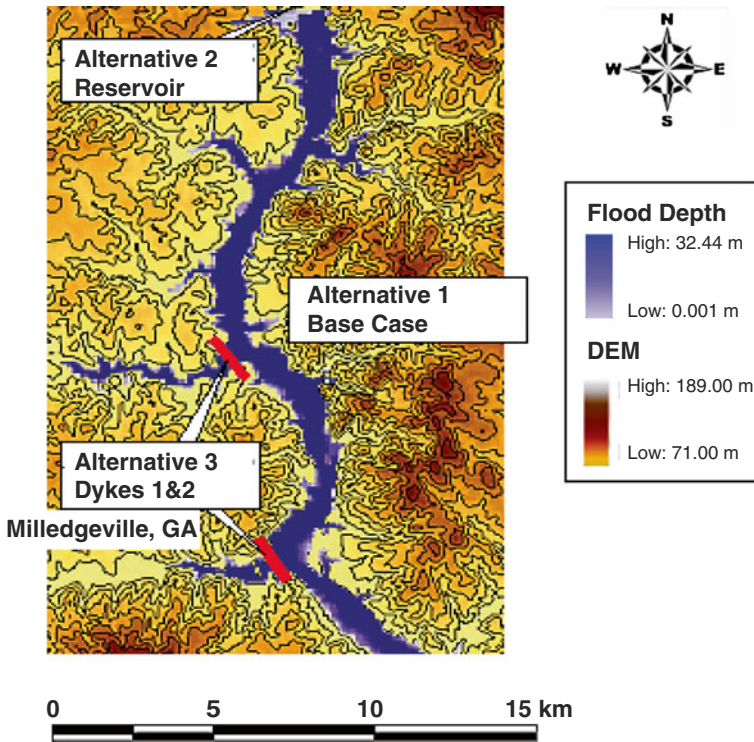


Fig. 5 Locations of Flood Protection Alternatives on Base Case 100-Year Inundation Map and DEM

4 Results and Discussion

In the present case study analysis (loss of life and urban flood damage analysis), each uncertain variable (or a variable with uncertainty) was assigned a probability distribution among the four distributions presented in Table 1 (e.g. normal, lognormal, triangular or uniform distributions). The parameters associated with the selected distribution are provided by the user through a graphical user interface. Based on the results of the 2D hydrodynamics analysis provided by CCHE2D-FLOOD, ArcMap functions were used to carry out a Monte

Table 2 Input data for loss-of-life estimation with probability distribution functions

Category	Name	Primary Value	Probability Distribution	Related Parameters
Flood Severity	High	> 6 m	Normal	<i>variance</i> =0.45
	Low	< 4.6 m	Normal	<i>variance</i> =0.6
Warning Time	Initial	20 min (after flood)	Uniform	<i>Range</i> (15, 35)
	Adequate	> 70 min	Uniform	<i>Range</i> (50, 90)
	No	< 25 min	Uniform	<i>Range</i> (15, 35)
Census	PAR	census raster	Normal	<i>Variance</i> = 8 % PAR
Fatality Rate	FR	default value	N/A	N/A

Table 3 Input data for urban flood damage analysis with probability distribution functions

Category	Name	Primary Value	Prob. Distribution	Related Parameters
High Intensity Residential Area (HIRA)	No of houses	15 Units	Triangular	$min=8, max=14$
	Structure value	\$ 150,000	Normal	$variance=0.35$
	Content value	\$ 95,000	Normal	$variance=0.25$
Low Intensity Residential Area (LIRA)	No of houses	8Units	Triangular	$min=4, max=10$
	Structure value	\$ 220,000	Normal	$variance=0.48$
	Content value	\$ 120,000	Normal	$variance=0.38$
Commercial Industrial Transportation Area (CITA)	No of houses	12 Units	Triangular	$min=6, max=12$
	Structure value	\$ 150,000	Normal	$variance=0.45$
	Content value	\$ 130,000	Normal	$variance=0.25$
	Other value	\$ 60,000	Normal	$variance=0.35$
Depth – % Damage Relationship	HIRA	$f=-0.68h^4+7.78h^3-34.52h^2+78.7h+4.95$	Triangular	$min=-5\%, max=+5\%$
	LIRA	$f=-2.61h^4+25.37h^3-78.42h^2+95.89h+4.31$	Triangular	$min=-5\%, max=+5\%$
	CITA	$f=-0.81h^4+9.25h^3-38.13h^2+71.20h+4.77$	Triangular	$min=-5\%, max=+5\%$

Carlo analysis by stochastic sampling of the uncertainty variables. Monte Carlo simulation of loss of life computation and flood damage computations were chosen to be 5,000 times based on the variable generated from Tables 2 and 3. The Monte Carlo analysis yielded the probability distribution functions of loss of life and flood damage in each cell, from which mean and standard deviation was calculated. The average results from the Monte Carlo simulation runs were obtained as the final decision criteria, and it was presented in the form of raster maps as an aid for better decision making related to flood hazard management.

The result image identifying the best alternative for each location is shown in Fig. 6. The larger the spatial extent of an alternative, the better the performance is. The spatial variability of each alternative represents the decision maker’s preferences of each criterion. Almost no region will benefit from Alternative 1 (smallest distance metric values occupying 24 cells), which is the base case with no flood protection measure. Alternative 2 (smallest distance metric values occupying 2,648 cells), 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 (smallest distance metric values occupying 274 cells)

Table 4 Criteria, weights and related CCHE2D-FLOOD results

Criteria	SMCA Used?	Weight	Related results from CCHE2D-FLOOD			
			Depth	Arrival Time	Duration	Velocity
Loss of life	Yes	0.4	X	X		
Flood damage	Yes	0.3	X			
Flood duration	No	0.15			X	
Flood power	No	0.15	X			X

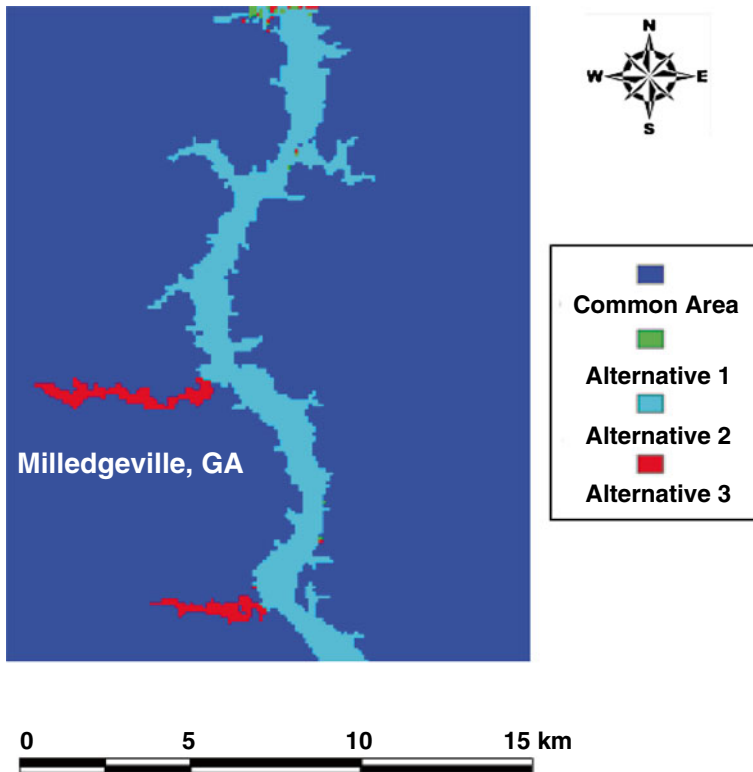


Fig. 6 Spatially Distributed Ranking of Alternatives Using SMCA

produces better results for the urban area since the dykes are effective in blocking the flood wave from entering in the urban area. The overall decision based on the above analysis is the alternative 3, since it is the most appropriate flood protection approach for the urban area.

When the ranked alternatives produced by the SMCA method are presented, it is found that it provides decision makers the ability to have more definition, diversity and discrimination in terms of the best strategies for particular spatial locations. This occurs because SMCA considers distance metric values spatially at each grid cell in the area, whereas the traditional Compromise Programming method calculates the average value of distance metrics throughout the whole region. Overall, the case study results seem to suggest the SMCA method is a competitive method for evaluating floodplain alternatives. It gives abundant information allowing the decision maker to more accurately discriminate among the best alternatives under investigation.

5 Conclusions

Natural disasters like flood are complex spatial phenomenon. In this research, an effective MCDM technique, SMCA is implemented as a comprehensive toolbox in widely used GIS software, ArcGIS to achieve the comparisons of various flood management alternatives. This toolbox takes the computational results from CCHE2D-FLOOD model as raster layers,

and makes use of multiple GIS feature layers and remote sensing images as reference layers to calculate the loss of life and economic damage from flood events. Various other criteria stream power “ $U \times V$ ” can be built using the interfaces of the toolbox, and different preferences of these criteria from decision makers can be taken into account. Raster layer computations and ranking the alternatives in ArcGIS environment make the evaluation process efficient and reliable.

The result from the case study clearly indicates the great effectiveness of this toolbox in facilitating flood management decision making. The spatial variability of each alternative is addressed, as well as the uncertainties involved in the analysis, so the most appropriate alternative for the area can be selected. This toolbox can serve not only flood protection planning purposes, but also be used to evaluate a large variety of natural resources management problems like forest management, agricultural land use planning, wetland planning and many others.

The CCHE2D-FLOOD simulation is performed for each pixel from the marginal distributions listed in Tables 1, 2 and 3; even though the spatial variability is accounted for in some extent by the parameter stratification, the random number generation is driven by some spatial dependence as it is reasonable that high marginal quantities in a pixel would correspond to high marginal quantities in the nearby pixels. The SMCA tool is specifically developed for CCHE2D-FLOOD, but can be extended for other models in the future.

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