DISSERTATION

METHODOLOGY FOR EVALUATING FLOOD DAMAGE REDUCTION ALTERNATIVES USING A GIS-BASED MCDA INTERACTIVE MODEL

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Kwang-Suop Lim

Department of Civil and Environmental Engineering

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY KWANG-SUOP LIM ENTITLED METHODOLOGY FOR EVALUATING FLOOD DAMAGE REDUCTION ALTERNATIVES USING A GIS-BASED MCDA INTERACTIVE MODEL AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

Luis Garcia

Dr. Luis A. Garcia

Evan Vlachos

Dr. Evan C. Vlachos

Darrell G. Fontane

Dr. Darrell G. Fontane
Adviser

Neil S. Grigg

Dr. Neil S. Grigg
Co-Adviser

Luis Garcia

Dr. Luis A. Garcia
Department Head

ABSTRACT OF DISSERTATION

METHODOLOGY FOR EVALUATING FLOOD DAMAGE REDUCTION ALTERNATIVES USING A GIS-BASED MCDA INTERACTIVE MODEL

Floodplain management involves the use of spatial physical information and information on decision makers' preferences. Both of these sources of information can have various degrees of imprecision. This research proposed a combined geographic information system (GIS) with Multi-Criteria Decision Analysis (MCDA). The use of GIS can give technical specialists and ultimately decision makers the possibility to find more spatially distributed information. These can be used to augment, an MCDA approach, which is an efficient tool for considering multiple-criteria in deciding on the best alternatives in a synthesized and integrated manner. The outcome of a floodplain management study is typically a recommendation for a single alternative flood management strategy. If this is developed by simply averaging over the entire floodplain, information is lost about the impact of the various alternatives on specific points in the floodplain. The ability to view this spatially distributed information could provide decision makers with a better understanding of the impacts of selected a specific alternative. Finally, a "cost of uniformity" metric is proposed that allows the decision makers to better determine the impact of selecting a single alternative for the floodplain by considering the spatially diverse information developed in the MCDA.

The target region for a demonstration application of the methodology was the Suyoung River Basin in Korea. The 1991 Gladys flood event and five different return periods were used as a case study to demonstrate the proposed methodology of evaluation of various flood damage reduction alternatives. Through a case study, the characteristics of four different MCDA methods and the impact of inserting additional criteria into the MCDA are examined and compared. Based upon the comparison between the methods, it has been illustrated that the Improved Spatial Fuzzy Weighted Average Method using an S-shaped Membership Function applied to adjusted digital elevation maps provides enhanced information for evaluating flood damage reduction alternatives.

Kwang-Suop Lim
Civil and Environmental Engineering Department
Colorado State University
Fort Collins, CO 80523
Spring 2008

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LIST OF ACRONYMS

CAD	Computer Aided Design
CP	Compromise Programming
DEM	Digital Elevation Model
DM	Decision maker
DTM	Digital Terrain Model
FDF	Frequency of Design Flood
GIS	Graphic Information System
GUI	Graphical User Interface
ISFWAM	Improved Spatial Fuzzy Weighted Average Method
MCDA	Multi-Criteria Decision Analysis
MOCT	The Korean Ministry Of Construction and Transportation
MODM	Multi-Objective Decision Analysis
MS	Management Science
OERI	Overall Existence Ranking Index
OR	Operations Research
SCP	Spatial Compromise Programming
SFWAM	Spatial Fuzzy Weighted Average Method
SMF	S-shaped Membership Function
TIN	Triangulated Irregular Networks
TMF	Triangular Membership Function

CHAPTER 1: FRAMING THE RESEARCH PROBLEM

1.1 Introduction

Amongst the wide variety of natural disasters a nation may experience, flood disasters occupy a very special place. Flooding is capable of causing enormous amounts of injuries, fatalities, and property damage, but it is the resulting economic and social disruption that sets flooding apart. Yalcin (2004) stresses that floods are the costliest natural hazard in the world and account for 31 percent of the total economic losses resulting from natural catastrophes. River flooding in particular has been a major natural hazard in recent events worldwide.

It has been shown that flooding problems can be solved, or at least substantially mitigated, by thorough floodplain studies and detailed project planning. It is therefore evident that determining the exact floodplain area is important to support decision makers in their planning and management activities (Yalcin and Akyurek 2004). Since one of the primary characteristics of floodplains areas is low vertical relief, vertical inaccuracies in the land surface elevation maps used for inundation mapping can result in relatively large inaccuracies in determining an area of flood inundation.

Jones et al (2001) notes that at the time many of the original flood inundation studies were conducted, the best available topographic map was a 1:24,000 scale map. Elevation data sets accurate to one foot would greatly improve the accuracy of flood maps and are necessary to sustain credible differences in 50- and 200-year flood maps whose flood levels may differ in elevation by less than one foot. Unfortunately, high accuracy maps with sufficient resolution within stream channels for hydraulic modeling are not widely available (Bedient and Huber 2002; Maidment 2002; Shim 1999; Tate et al. 2002; Zerger 2002). Given the absence of such high accuracy maps, current methods of estimating the depth of flood within a Geographic Information System (GIS) framework are inadequate (Jones et al. 2001; Jones et al. 1998; Tate et al. 2002).

The errors introduced by such inaccuracies contribute a degree of imprecision that can be associated with model results. Therefore, the role of errors in model inputs and model parameters which affect the outcomes of the floodplain management cannot be neglected. Hwang (2005) and Zerger (2002) note that these factors contribute to the overall imprecision in the results of flood management models.

Since one of the important objectives of floodplain management is to reduce the effect of inaccuracies or impression on the answer, the task of improving consideration of imprecision should be extended to the use of the GIS as well as the variety of spatial analysis techniques used within the context of Multi-Criteria Decision Analysis (MCDA). In order to ensure the most accurate decision-making possible regarding floodplain alternatives, it is important that the complete suite of software tools necessary to fully evaluate all options be available through one intuitive, graphical environment.

Several authors have suggested that there are grounds for believing that GIS has an important function to play in floodplain analysis because it is well suited to handling the multi-dimensional phenomena and spatial components that comprise floodplain analysis (Coppock, 1995; Zerger, 2002). The advantage having spatial data is that it allows the consideration of the unique characteristics at every location. The GIS provides the possibility to develop more spatially distributed information. Ultimately decision makers will typically select a single flood water management alternative (such as levees or a combination of levees and channelization) for the entire project region. The selected alternative will be more successful in minimizing flood impacts at some spatial locations than others. If the information developed is lumped over the entire floodplain, then the details of the information are lost.

For example, suppose that a floodplain has a large amount of farmland and a smaller urban area. Suppose that in terms of lower flood depths and time of inundation for the urban area, a combination of levees and channelization is the preferred alternative. However, for the farm land, the most preferred alternative is to use only levees. If the decision is made by simply integrating the information over the entire floodplain and the selection is based upon the largest area favoring a specific alternative, then the use of levees will be recommended to the decision maker. However, if the information is provided to the decision maker in a more spatially distributed format, then they can see that the urban area would be better served with the combination of levees and channelization option. This urban area might contain the hospitals and schools that support the entire farming region. This might lead the decision makers to ask for more information such as the increase in costs or increase in impacts for all locations of selecting one flood management alternative over the other. In other words, by providing more spatially diverse information, the decision makers can make a more informed decision. In this study, therefore, more diversity and discrimination is considered to be providing more detailed information and is preferred to less detailed information.

At this point it is important to clarify the use of the term “decision makers” in this dissertation. Often the term “decision makers” is narrowly defined to be the person or persons that ultimately make the final decision. Often this person may not be an engineer of have a technical background. A broader definition of “decision makers” includes the group of people who make the recommendations that ultimately go to the final decision maker. This group includes the engineers and technical specialist that use the models and synthesize the results to support the final decision. The methodology presented in this research is targeted toward technical users. This study shows examples of how the details of the analysis might be synthesized so that the final decision maker can make a more informed decision.

Rejeski (1993) claims that GIS spatial analysis techniques may introduce problems unique to the technology during the data integration and analysis process. Moreover, floodplain management problems tend to be complex and multi-faceted, requiring an MCDA approach. MCDA allows decision makers to consider multiple-criteria in deciding on the best alternatives. The combinations of spatial and multi-criteria provide the ability to have even more definition and discrimination in terms of the alternatives that might be best for particular spatial locations. Again, more discrimination is taken to mean more information and this is considered highly desirable.

It is necessary to address these issues in a synthesized and integrated manner (Shrier 2004). A Graphical User Interface (GUI) is a good way to help decision makers make an integrated analysis.

This research is focused on addressing questions pertaining to the methodology of floodplain analysis using GIS and MCDA to evaluate flood damage reduction alternatives. These issues and the approaches used to address them have been outlined in the following points.

- In places where a stream channel is very flat, a mere one-meter increase in water level may result in the inundation of a very large area extending hundreds of meters away from the river channel. Accurate floodplain elevation data is required to represent the terrain in such an inundation simulation (David, 2000). Adjusted terrain maps with increased spatial accuracy over traditional Digital Elevation Models (DEM) should be used as base maps for evaluating various floodplain alternatives.
- Analyses using conventional MCDA techniques are often limited by the ability to capture the spatial variability of a region, which affects the decision-making information for floodplain management throughout the basin.
- Imprecision is inherent in the representation of any natural process. Fuzzy theory offers a way to consider the various parameters of a model, criteria values, rating scales, and decision makers' preferences as numbers that have uncertainty, vagueness, or imprecision.
- MCDA approaches to evaluate various alternatives have so far been applied with just a few criteria. However, adding more and different criteria may produce more diversity or less diversity of the preferred options. There is a need to see how multiple criteria might affect the discrimination of options.
- A clear need exists for a systematic, interactive, and transparent MCDA procedure available from within a user-friendly application capable of enhancing the decision maker's perception of the problem. An easy to use Graphical User Interface (GUI) is the best candidate for such an application.

The aforementioned questions and issues will be examined in a case study of the Suyoung River Basin in Pusan, Korea. The rest of this chapter is organized as follows. A short background of the entire research is presented in the second section, and the framework of the entire research will follow in section 3. In section 4, the methodology of the research will be explained. An overview of the research outcomes and the contributions are discussed in section 5.

1.2 Background and research problems

As mentioned previously, determining the floodplain area is important for floodplain decision makers' planning and management activities (Yalcin and Akyurek 2004). It is widely known that floodplains are characteristically low relief, and vertical inaccuracies in a land-surface elevation map used for inundation mapping can result in relatively large inaccuracies in mapping an area of flood inundation.

In the absence of a high accuracy map as the source of the cross-sectional descriptions needed for calculating flood water depth, current methods of estimating the depth of a flood within a GIS are inadequate (Jones et al. 2001; Jones et al. 1998; Tate et al. 2002). A method of creating an adjusted stream channel DEM for floodplain analysis from existing cross-sectional data may result in significantly reducing the imprecision which comes from low accuracy maps, and can also save both time and resources (Shrier 2004; Tate et al. 2002; Zerger 2002).

Compromise Programming (CP) is a mathematical programming method used in a multiple objective context (Zeleny 1973; Zeleny 1974; Zeleny 1982). The compromise solution identified to be closest to the ideal solution and constituting the compromise set can be determined by calculating the distance of each alternative from the ideal solution and selecting the alternative with the minimum distance as the compromise solution (Goicoechea et al. 1982). It is important to note that the CP method does not apply a spatial variable to the criteria values. Therefore, in identifying the best alternative using CP, only the region as a whole is considered, and local impacts associated with different alternatives are possibly ignored. Consequently, the alternative identified as the best for an entire region by a CP method may not be the best for all locations within that region (Nirupama and Simonovic 2002). The point is that without accounting for spatial variation, the criteria values may inadvertently result in a considerable amount of missing information.

This spatial variability in the criteria values associated with the various alternatives is introduced by combining the CP method with GIS technology. This combination is called Spatial Compromise Programming (SCP). It first appeared in the work of Tkach and Simonovic (1997). The region of interest encompasses all geographic locations which are impacted by a combined group of alternatives. In the SCP approach, the region is represented by a grid feature image of the study area. Within the feature image, an individual grid cell represents each location for which a distance metric is calculated (Nirupama and Simonovic 2002). Spatial analysis with GIS makes it possible to discriminate and determine whether some options are better in particular areas versus others. However, SCP is unable to address the effect of imprecision in model parameters, criteria values, equipment accuracy, or lack of knowledge that also contribute to complexity in the decision-making process.

The Spatial Fuzzy Weighted Average Method (SFWAM) is a technique developed by Bender and Simonovic (2000) which transforms a distance metric into a fuzzy set. This is accomplished by changing all the inputs from crisp to fuzzy and applying the fuzzy extension principle (Bender and Simonovic 2000). Spatial analysis with consideration of imprecision actually may give more or less diversity and spatial distribution of the best alternatives. Fuzzy theory offers a way to represent and handle imprecision.

Integration of the SFWAM through a GUI application using an adjusted DEM as a base map can address the desired spatial variability and imprecision in the flood management process. The importance of keeping high-resolution flood maps cannot be overemphasized since the flood map itself also affects the results of the MCDA. In addition, the GUI offers advantages of time savings, error checking, improved control, and increased understanding of the overall procedures for evaluating floodplain alternatives by guiding the user through the various tasks. The decision maker will have more assurance of his or her decision using the integrated display system, which shows graphically the results of each alternative.

1.3 Proposed framework

The following framework (Figure 1.1) is proposed to address the problems in floodplain management support using selected MCDA techniques.

- Present and discuss the advantages and limitations of different accuracies of stream channel data in DEM, and improve the accuracy of the flood maps by integration of hydraulic model data. Compare the performance for flood maps in the basin by comparing an adjusted DEM that couples surveyed cross-sectional data with an unadjusted DEM.

- Develop a standard metric for measuring or quantifying the flood inundation area as compared with an actual flood map.
- Develop flood damage reduction alternatives and criteria to evaluate these alternatives.
- Compare the results produced by different MCDA methods.
- Add additional criteria and compare with the previous research methods which used two criteria (flood water depth and flood damage), determine the impact of inserting additional criteria on the results of the MCDA technique, and test whether more criteria produce more or less diversity of preferred options.
- Evaluate and suggest a methodology of implementing a combination of GIS and MCDA techniques for floodplain analysis.

1.4 Methodology

1.4.1 The use of GIS to manipulate DEM

A grid of regularly spaced elevation data, a DEM, is commonly used in hydrologic analyses to represent flow paths of water over land. In many of the hydraulic models, flood inundation areas were frequently mapped using lower accuracy maps such as 50- and 100-*m* gridded DEMs. These are derived from the elevation contours on 1:24,000 scale quadrangle maps and have a vertical accuracy of half of a contour interval (typically 20-feet). However, according to Jones et al (2001) this vertical accuracy is not sufficient for delineating inundations for flood stages that may differ by as little as 1*m*. For example, the average difference in flood water depth for the 10-year and 200-year floods of Korea's

Suyoung River is 0.998*m*. Modified stream channel DEMs are derived from cross-sectional data stored in the U.S. Army Corps of Engineers Hydrologic Engineering Center River Analysis System (HEC-RAS). Hydraulic models and comparisons of performance and characteristics of the flood inundation mapping are made using the HEC-GeoRAS with different DEM scales.

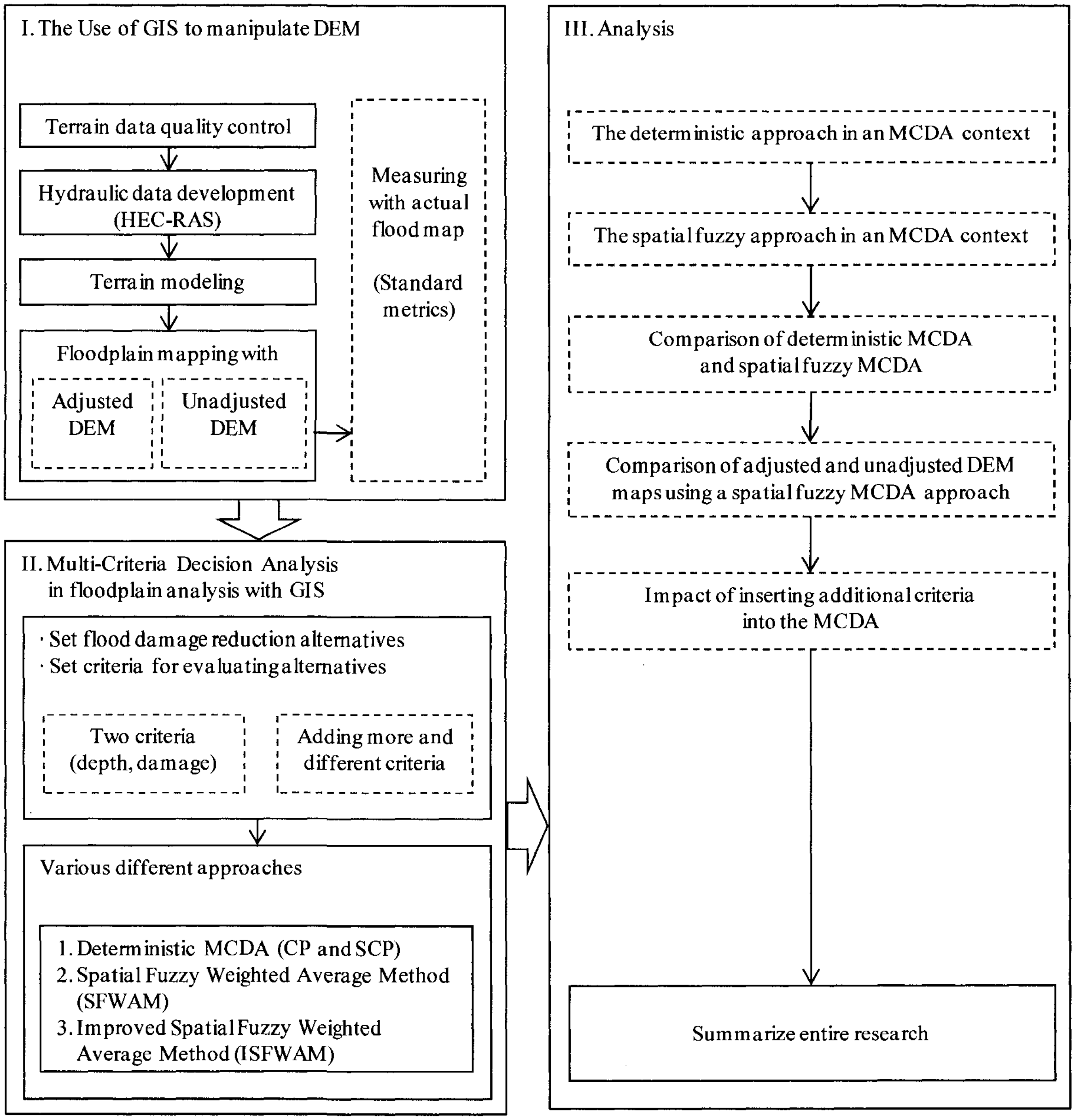


Figure 1-1. Conceptual diagram of a GIS-based MCDA interactive model for evaluating flood damage reduction alternatives using GIS and MCDA

1.4.2 Multi-Criteria Decision Analysis (MCDA) in floodplain analysis with GIS

Decision-making is a choice or selection of alternative courses of action in many fields, both the social and natural sciences. The unavoidable problems in these fields necessitate detailed analysis that consider a large number of different criteria, all of which need to be evaluated during decision analysis (Yalcin and Akyurek 2004). In the most general terms, MCDA problems involve a set of alternatives that are evaluated on the basis of conflicting and incommensurate criteria.

In this research, to alleviate the flood damage produced by flooding in the Suyoung River Basin, a number of flood damage reduction alternative implementations are considered. These alternatives are: no action in which it is to leave the floodplain area as it is with no additional action, build a levee around the community that needs to be protected, channelization, pumping, and a combination of channelization and pumping. Five criteria that exhibit a spatial variability are then selected for evaluating the flood damage reduction alternatives: flood water depth, flood damage, land use disruption, risk of flooding under different return periods, and drainage capacity. The computational procedures are necessary to produce the grid criteria images for both the deterministic and spatial fuzzy approach in an MCDA context.

The first criterion used in the evaluation of the alternatives is the floodwater depth for the study region. An image is prepared in which each grid cell contains the water depth for all distinct geographic locations. This is accomplished by using a combination of flooded feature images, the water surface elevations as contained in the image, and the DEM of the region of interest. For all flooded areas, as indicated by the flooded feature image, the ground surface elevations in the DEM are subtracted from the simulated water surface elevation. Grid cells in locations which were unaffected by floodwaters retain a value of zero or negative. In this way, an image containing the water depths for all flooded locations in the study region is produced for each floodplain alternative (Nirupama and Simonovic 2002).

The second criterion used in the evaluation of the alternatives is the dollar value of damage under different return periods within the region of interest.

The third criterion is the land use disruption of the studied area. Land use disruption will be considered differently than the monetary flood damage. As an example, if flooded areas contain structures that might have a high population of people, such as housing, industrial buildings, hospitals, etc., then the area will have a higher avoidance value than farmland. The land use disruption as a criterion could also take into account disruption or interruption of services because of flooding.

The fourth criterion is the risk of flooding under different return periods. This criterion varies with different kinds of flood damage reduction alternatives. The final criterion is the drainage capacity. Different types of soil have different capacities for retaining rainwater.

Different weighting sets, which describe the decision maker's preferences towards the criteria, will be applied when performing the deterministic and spatial fuzzy MCDA analyses. In order to represent the potential different opinions of the various groups of interested decision makers in this research, six different sets of weights were selected for the criteria.

The combination of GIS and MCDA capabilities is of critical importance in spatial multi-criteria analysis. The advantage of having spatial data is that it allows the consideration of the unique characteristics at every point. However, GIS systems have a limited capability as far as the analysis of the value structure is concerned. The MCDA techniques provide the tools for aggregating the geographical data and the decision maker's preferences into a one-dimensional value for analyzing alternative decisions (Malczewski 1999). In other words, the MCDA allows multiple criteria to be used in deciding upon the best alternatives. Though SCP is capable of accounting for the spatial variability factor, it is unable to address various imprecision associated with a complex system of multiple alternatives, multiple criteria, and multiple decision makers (Nirupama and Simonovic 2002). Imprecision in model assumptions, data, or parameter values, also contribute to the complexity in decision-making process (Hwang 2005). In order to offset this disadvantage, the effect of various imprecision on the results could be reduced by applying the SFWAM technique. Thus, integration of SCP with fuzzy set theory can provide the ability to have more definition and discrimination in terms of the best alternatives for particular spatial locations and address imprecision in the flood management process. While this inherently includes another imprecision arising from the lower accuracy DEM data, coupling the adjusted DEM and SFWAM techniques has the potential to show greater diversity and greater spatial distribution of the best alternatives.

1.5 Expected outcome and key contribution

The objective of this study is the development of a methodology that improves upon recent approaches of floodplain management using an integrated GIS and spatial fuzzy MCDA technique. This research will enhance floodplain analysis by integrating several advanced technologies into an MCDA framework, improving definition and representation of flood maps, making more extensive use of differing criteria for evaluation of the effect of additional criteria on the solutions, analyzing how both individual criteria and numerous criteria might affect the diversity and discrimination of options, and comparing different types of MCDA techniques.

The proposed approach involves integrating a hydraulic model's terrain data with lower accuracy DEM for flood maps, implementation of deterministic MCDA techniques, and implementing a combination of GIS and fuzzy MCDA into floodplain decision making. The specific objectives of this dissertation are follows:

This dissertation will make the following key contributions:

- Provide comprehensively reviewed research on GIS for integrating surveyed cross-section data with lower accuracy DEM, and offer insights into the advantages and limitations of various MCDA techniques for evaluating flood damage reduction alternatives.
- Produce adjusted DEM's by combining an unadjusted DEM with existing surveyed stream channel elevation data. The adjusted DEM's also represent the general landscape and are comparable in quality to aerial photogrammetry. These will provide measurable improvement in floodplain mapping for use with MCDA techniques and give the decision maker the capability to better decide the preferred flood damage reduction strategies.
- Present the development of a GIS-based MCDA interactive model that is transparent and easy for a decision maker to use. This provides an automated process of alternative evaluation and selection within a flexible, fully integrated interactive system. By graphically presenting the results of each simulation, the

implications of each alternative can be easily understood.

- Showed that among MCDA methods for flood management purposes, the spatial fuzzy approach method gives the most diversity in the flood damage reduction alternatives. The performance of the ISFWAM method coupled with an adjusted DEM in a GIS environment is compared with other commonly used MCDA techniques. This research showed how this approach improved the capability to show greater diversity and greater spatial distribution of the best alternatives.
- Demonstrated the impact of adding additional MCDA criteria. Current research shows MCDA for flood damage has been applied using only a few criteria (only flood water depth and flood damage) but for better results the MCDA approach needs to apply more criteria for evaluating the alternatives. By adding additional criteria into MCDA, the capability to make the best alternatives more diverse and show the decision maker more differences in the scores of the alternatives to allow the decision maker to discriminate is significantly improved.
- Proposed the development of a "cost of uniformity" metric that allows decision makers to compute the impact of selecting a single alternative for the entire floodplain. This metric represents the increase in the average distance metric value as compared to the spatially diverse solution from the MCDA and GIS analysis.

The rest of the thesis chapters are organized as follows. The second chapter gives an in-depth literature review of pertinent topics such as floodplain management, GIS, MCDA, and GIS-based MCDA. In chapter 3, the methodology of the research will be explained. In chapter 4, various MCDA approaches are used to evaluate candidate alternatives using a GIS-based MCDA model based upon a variety of performance comparisons and adjusted DEM's. Summary and discussions follow in chapter 5. Lastly, a list of references used in the research is presented at the end of the dissertation.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Flooding and its associated damages have been with us throughout history. Leopold et al. (1964) defines flooding as a natural and recurring event for a river or stream and is a result of heavy or continuous rainfall exceeding the absorptive capacity of soil and the flow capacity of rivers, streams, and coastal areas. This causes a watercourse to overflow its banks onto adjacent lands. In another aspect of the definition of flooding, however, Hoggan (1997) defines flooding with a slightly different point of view:

> "*The nature of floods and their impact depend on both natural and human-made conditions in the floodplain. Economic development and the installation of flood protection measures have political, economic, and social dimensions as well as engineering aspects. Hydrologic and hydraulic analysis of floods provides a sound technical basis for management decision-making that must weigh numerous other factors.*"

Both of the definitions emphasize certain critical aspects of flooding, such as the general meaning of flooding and flood protection measures (Bedient and Huber 2002). Now people have begun recognizing the importance of an integrated approach which can reduce the undesirable effects upon life and property from flooding. However, these definitions do not take into account the role of a more integrated flood defense and management approach. Consequently, the simple flooding definition needs to be expanded to include the aspect of flood control and floodplain management. As Grigg

(1996) insists, although water resources decision maker must control floods and prevent damage from flooding, this is a different type of mission than providing a water supply or controlling water quality: it is a protective mission. With this aspect, Hoggan (1997) defines before many recent authors (e.g. Kundzewicz 2002, Simonovic 2002, UNSEOP 1994) and research centers discussing general flood management by emphasizing a more integrated approach, including measures such as insurance, inundation estimation, forecasting, warning and land use planning.

2.2 Floodplain management

On an overall basis, according to recent media, statistical and historical data, floods can be a terrifying disaster faced by many countries. Floods cost many millions of dollars every year in property damage, lost production, lost wages, and lost business. These can be enormously expensive and still there is no sure guarantee of protection. Water resources managers must control floods and prevent damage from them. Grigg (1996) stresses that it is a defensive assignment to the water resources decision maker. This means that floodplain management and flood control incorporate an integrated approach towards protecting the floodplain from further damages. It entails dealing with existing flooding problems and eliminating increases in the level of potential damage from further development. Flood control typically involve a mixture of land use and water management for identified floodplains, and as a result involve political issues related to land use (Grigg 1996).

The Floodplain Management Association defines the approaches which are used in floodplain management, and there are a wide range of approaches that can be used to protect against flooding problems. Flood control measures may be classified into categories in various ways, such as structural and nonstructural approaches, whether or not the control measures are most suitable for protecting: (1) individual structures or (2) areas containing multiple structures and communities, and whether the purpose is to: (1) modify the flood; (2) reduce susceptibility to flooding; and/or (3) reduce the impact of flooding.

In order to lessen the effects of flooding, the first reaction in the past was to build levees or dams. However, this has often caused a false sense of security and encouraged further development in the floodplain environment. However, floods continued to increase despite the construction of dams and levees, which all too frequently did not hold back the flood waters. The Congress of the United States was determined to look at alternative means of floodplain management and to reduce the ever increasing property damage from floods (Krimm 1998). The flood control system in the Upper Mississippi River Basin worked during the 1993 flood; and, in fact, the overall flood control system of the United States has paid for itself seven times since the 1993 flood.

On the other hand, certain so-called nontraditional flood management techniques appear to need more emphasis. Techniques such as improving flood forecast methods, flood proofing, and/or controlling what is built in flood-prone areas should be included as tools used to reduce future flood damages (Lovelace and Strauser 1998). When these techniques were introduced, people began to understand that controlled and expanded floodplain analysis could reduce flood disasters. Now most developed countries, especially the U.S., have turned their attention to nonstructural measures of flood management (Shim 1999). Flood mapping is one of the non-structural measures to protect human lives and properties from flood disasters. It is the least costly method of flood damage reduction, if implemented prior to major flooding.

Flood mapping in Korea originated from a report, "White Book of the Comprehensive Planning for the Flood Disaster Prevention (1999, President's Task Force Team for Flood Disaster Prevention)." The report includes various flood protection and mitigation programs covered from ranging the engineering technologies to budgeting (Koh 2004).

2.3 Geographic Information System (GIS)

A Geographic Information System (GIS) is a system for capturing, storing, analyzing and managing data and associated attributes, which are spatially referenced to the earth. In the strictest sense, it is a computer system capable of integrating, storing, editing, analyzing, sharing, and displaying geographically referenced information. In a more generic sense, GIS is a tool that allows users to create interactive queries (user created searches), analyze the spatial information, edit data, maps, and present the results of all these operations (http:// erg.usgs.gov /isb/pubs/gis_poster/index.html).

GIS has evolved out of a long tradition of map making. In many respects, modern GIS dramatically increases the amount of information that can be contained and manipulated in a map. On the other hand, many of the same cartographic conventions and limitations apply to digital maps (James 2001). Like all models, maps are, by necessity, simplified representations of reality. Partly, this is for convenience; it becomes very difficult to draw and interpret multiple information themes on one map covering more than a very small area (Monmonier 1996). Before computers became widely available, thematic maps on plastic Mylar sheets could be laid on top of each other, revealing more information about an area than was possible with any single paper map. Ian McHarg's classic landscape architecture text, *Design with Nature*, advocated a rational approach to site planning by creating Mylar overlays depicting landforms, soil types, vegetation patterns, and geomorphic features (McHarg 1992). Although the process was cumbersome and the amount of data limited, McHarg's method looks remarkably like the output of contemporary GIS; colored thematic maps were generated that aided in planning. However, as Burrough and McDonnell (1998) note with all of these early systems "The paper map and its accompanying memoir was the database." But the main problem of a paper map is that there can be no database of information directly linked to the paper map and no automation of spatial querying (James 2001). The history of using computers for mapping and spatial analysis show that there have been parallel developments in automated data capture, data analysis, and presentation in several broadly related fields such as cadastral and topographical mapping, civil engineering, mathematical studies of spatial variation, and remote sensing and image analysis. Essentially, all these disciplines are attempting the same sort of operation - namely to develop a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a particular set of purposes (Burrough 1993; Shim 1999). Antenucci and Brown et al. (1991) explained that early GIS packages were often written for specific applications and required the mainframe computing systems found usually in government or university settings. In the 1970s, private vendors began offering off-the-shelf GIS packages. M&S Computing (later Intergraph) and Environmental Systems Research Institute (ESRI) emerged as the leading vendors of GIS software. In the late 1990s, GIS was being adopted slowly on the sub-municipal level by neighborhood organizations and community-based agencies. The development of ArcView for Microsoft Windows and ArcIMS, which enables distributed mapping and spatial analysis over the Internet and eliminates many of the hardware and licensing expenses of a full software package, has increased the availability of spatial data to marginalized and underfunded groups. Although access to both GIS software and spatial data sets has improved, the adoption of GIS as a planning or research tool still represents a significant commitment by community organizations (Spicer 2000).

It was previously noted that GIS is a system of hardware and software used for storage, retrieval, mapping, and analysis of geographic data. Practitioners also regard the total GIS as including the operating personnel and the data that goes into the system. The important thing is that spatial features are stored in a coordinate system, which references a particular place on the earth. Descriptive attributes in tabular form are associated with spatial features. Spatial data and associated attributes in the same coordinate system can then be layered together for mapping and analysis. From a spatial point of view, GIS differs from Computer Aided Design (CAD) and other graphical computer applications in that all spatial data is geographically referenced to a map projection using an earth coordinate system.

Presently, many GIS applications in water resources decision making are frequently used to make decisions related to the spatial variability of data by different research groups. Because of the spatial nature of the required data (Tsihrintzis et al. 1996), GIS technology effectively facilitates the decision making process in water resources modeling. In addition, many of the GIS systems are equipped with a GUI, which increases the decision maker's comprehension of the spatial information that is involved in the problem being addressed. A GIS can offer an effective spatial data-handling tool that can enhance water resources modeling through interfaces with sophisticated models. Kaden (1993) showed in full detail that specific planning and management tasks for which a GIS with a GUI may be of assistance are: comparative analysis, monitoring of dynamic processes, evaluation of current conditions, detection of changes, forecast of future developments, problem assessment, planning of action (e.g., mitigation), identification of regions that meet multiple criteria (e.g., site selection), identification and allocation of resources, analysis of floodplains and the determination of cumulative effects based upon spatial location.

2.4 Multi-Criteria Decision Analysis (MCDA)

In practice, flood management decision-making attempts to minimize the flood damage; to minimize the depth of floodwater in floodplain area; and to minimize the flooding time to help to victims. These problems are usually too complex and ill-structured to be considered through the examination of a single criterion, attribute, or point of view in the hope that it will lead to the best decision (Zopounidis and Doumpos 2006). In fact, such a one-dimensional approach is merely an oversimplification of the actual flood problems at hand, which can lead to unrealistic decisions. A more appealing approach would be the simultaneous consideration of all proper factors that are related to the actual floodplain management problem. However, through a one-dimensional approach some very essential questions emerge;

- How can several (often conflicting) factors be aggregated into a single evaluation model?
- Is this evaluation model a unique and optimal one?

Relevant to this point, Zopounidis and Doumpos (2006) note that researchers from a variety of disciplines have tried to address the first question using statistical approaches, fuzzy and artificial intelligence techniques, and operations research methodologies. The success of these attempts should be examined with regard to the second question. Obviously, not all decision makers address a decision problem in the same way. Each decision maker has his or her own preferences, experience, and decision-making policy; thus, one person's judgment is expected to differ from another person. This significant issue should be considered during the development of decision-making models.

Addressing such issues constitutes the focal point of interest in MCDA. MCDA constitutes of an advanced field of operations research that is devoted to the development and implementation of decision support tools and methodologies to confront complex decision problems involving multiple criteria, goals, or objectives of conflicting flood problems. The tools and methodologies provided by MCDA are not just some mathematical models aggregating criteria, points of view, or attributes, but furthermore are decision support oriented. Support is actually a key concept in MCDA, implying that the models are not developed through a straightforward sequential process where the decision maker's role is passive. Instead, an iterative process is employed to analyze the preferences of the decision maker and represent them as consistently as possible in an appropriate decision model. This iterative and interactive preference modeling procedure constitutes the underlying basis of the decision support orientation of MCDA. It is one of the basic distinguishing features of the MCDA as opposed to conventional statistical and optimization decision making approaches (Gale 2006).

Applications of MCDA to water resources planning and management have come a long way since the work of explicit form by Harvard Water Programming, and much of the methodology and research findings were published by Mass et al. (1962) and Cohon and Marks (1973), who made an evaluation of multi-objective programming methods as linear programming vector optimization problems. There also exist methodologies based upon multi-attribute utility theory based upon the work of Raiffa (1968), where explicit trade-offs between attributes are utilized. Other popular techniques used for discrete alternative selection include the Surrogate Worth Trade Off (Haimes 1998), ELECTRE (Roy 1971), Analytical Hierarchy Process (Saaty 1980), and Compromise Programming (CP). The PROTRADE method (Goicoechea et al., 1982) included for the first time imprecision into the MCDA. More recently, Nirupama and Simonovic (2002) apply the concept of Spatial Fuzzy Compromise Programming (SFCP) for solving spatial variability and fuzzy theory to the problem of imprecision. They try to reduce the imprecision by using a spatial fuzzy compromise approach. Now, as a consequence, MCDA is adapted by most water resources divisions for tasks such as river basin planning, conjunctive water use, reservoir operation, water quality management, water and related land resources and floodplain management because the use of natural resources has wide reaching impacts on human needs, both for survival and for economic purposes (Shrier 2004).

2.5 GIS-based Multi-Criteria Decision Analysis

For the best strategies of flood management, comprehensive, coordinated, and sustainable projects should consider spatial homogeneity problems. Although there are many enhanced and emergent MCDA technologies in the world, the water resources decision maker must make the best decision within their area of interest. Unfortunately, the water resources decision maker may be faced with overcoming spatial limitations in order to provide the optimum strategy. Many researchers (Bender and Simonovic 2000; Malczewski 1999; Nirupama and Simonovic 2002; Simonovic and Nirupama 2005; Simonovic 2002; Tkach and Simonovic 1997) insist that conventional MCDA techniques such as Compromise Programming (CP) have largely been spatial in the sense that they assume a spatial homogeneity within the study area. This assumption is unrealistic in many decision situations because the evaluation criteria vary across space.

It is difficult and complicated to select the best strategy or decision-making process from a number of potential alternatives for floodplain management. Moreover, most of the planning is done without considering spatial heterogeneity and the imprecision involved with such complex processes. Integrating MCDA with a GIS (Malczewski 1999) is called spatial MCDA, and provides a framework for incorporating preferences into GIS procedures. It is capable of aggregating the geographical data and decision maker's preferences into one-dimensional values representing alternative decisions. Therefore, the combination of GIS and MCDA technique is a powerful tool for assisting water resources decision maker's strategy selection.

CHAPTER 3: METHODOLOGY

3.1 Introduction

The purpose of this chapter is to identify, review, and evaluate the performance of a number of various MCDA techniques for integration with GIS. Even though there are a number of techniques which have been applied in many fields, this research will only consider the techniques that have been applied in floodplain decision-making problems. Four different methods for multi-criteria evaluation were selected to be integrated with GIS. These four algorithms are Compromise Programming (CP), Spatial Compromise Programming (SCP), Spatial Fuzzy Weighted Average Method (SFWAM), and Improved Spatial Fuzzy Weighted Average Method (ISFWAM). Detailed concepts of these algorithms are presented in this chapter.

The rest of this chapter is organized as follows. Section 2 provides a general review of GIS and section 3 discusses a number of MCDA techniques to describe theoretical aspects and limitations of applied methods. Lastly, fuzzy set theory is discussed in section 4.

3.2 Geographic Information System (GIS)

The input data to a floodplain management model to optimize the location of a particular mitigation facility requires a large amount of spatial data analysis. The spatial analysis with GIS makes it possible to discriminate and determine which alternatives are better in particular areas versus others. Hence, this leads to the consideration of using GIS. A typical GIS can be understood by the help of various definitions as follows: GIS is a computer-based tool for mapping and analyzing things that exist and events that happen on Earth. Burrough (1986) defined GIS as a "set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a particular set of purposes." Aronoff (1993) defines GIS as, "a computer based system that provides four sets of capabilities to handle geo-referenced data: data input, data management (data storage and retrieval), manipulation and analysis, and data output." Hence, a GIS is looked upon as a tool to assist in decision-making and management of attributes that need to be analyzed spatially.

The use of GIS has been in vogue primarily due to following advantages: (1) project planning, (2) making better decisions, (3) visual analysis, (4) improving organizational integration, (5) manipulation of spatial data and the corresponding attributes, and (6) integration of different types of data in a single analysis at high speed. Put simply, GIS data represents real world objects (infrastructures, soil type, roads, land use, elevation) with digital data. Real world objects can be divided into two abstractions: discrete objects (a house) and continuous fields (rainfall amount or elevation).

For representing spatially distributed information of both types, it is necessary to have the fundamental components of spatial data in a GIS data model. These are typically based upon both raster and vector data. The raster data type consists of rows and columns of cells wherein a single value is stored in each cell. Most often, raster data sets are raster images, but besides just color, the value recorded for each cell may be a discrete value, such as land use, a continuous value such as rainfall, or a null value if no data is available. The resolution of the raster data set is its cell width in ground units. The vector data type uses geometries such as points, lines, or polygons to represent objects. Vector data can be used to represent continuously varying phenomena. Contour lines and Triangulated Irregular Networks (TIN) are used to represent elevation or other continuously changing values. TINs record values at point locations, which are connected in turn by lines to form an irregular mesh of triangles. The face of the triangles represents the terrain surface. Additional non-spatial data can also be stored besides the spatial data represented by the coordinates of vector geometry or the position of a raster cell. In vector data, the additional data are attributes of the object. For example, a forest inventory polygon may also have an identifier value and information about tree species. In raster data, the cell value can store attribute information, but it can also be used as an identifier that can relate to records in another table. There are advantages and disadvantages to using a raster or vector data model to represent reality. Raster data sets record a value for all points in the area covered which may require more storage space than representing data in a vector format that can store data only where needed. Raster data also allows the easy implementation of overlay operations, which are more difficult with vector data. Vector data can be displayed as vector graphics used on traditional maps, whereas raster data will appear as an image that may have a blocky appearance for object boundaries. Vector data can be a lot easier to register, scale, and re-project. This can make it much simpler to combine vector layers from different sources. Vector data are more compatible with relational database environment. They can be part of a relational table as a normal column and processed using a multitude of operators (http://en.wikipedia.org/wiki/Gis).

A fully functional GIS is an integration of several components and different subsystems (see e.g., Maguire et al. 1991; Burrough and McDonnell 1998; Longley et al. 1999). It is devoted especially to collecting, storing, retrieving, and analyzing spatially referenced data. Even though numerous practical applications have shown that GIS is a powerful tool of acquisition, management and analysis of spatially referenced data, most current Operations Research (OR) or Management Science (MS) specialists (e.g. Janssen and Rietveld 1990; Carver 1991; Fischer and Nijkamp 1993; Laaribi et al. 1993, 1996; Malczewski 1999; Laaribi 2000) share the impression that the GIS is a limited tool in the spatial decision-aid domain. This is due essentially to its lack of more powerful analytical tools enabling it to deal with spatial problems involving several parties with conflicting criteria.

Among the criticisms that have been directed at GIS technology, this research enumerates the following examples (Burrough 1990; Janssen and Rietveld 1990; Carver 1991; Goodchild 1992; Laaribi et al. 1993; Laaribi 2000):

The decision maker's preferences (e.g. criteria weights) are not taken into account by current GIS. Some raster-based GIS, however, allow ratios for criteria (e.g. starting with Version 4.1, the IDRISI GIS supports the Analytic Hierarchy Process (AHP) method of (Saaty 1980) for computing criteria weights) but these ratios are usually introduced prior to the solution generation process, i.e., in a non-interactive manner.

In most GIS packages, spatial analytical functionalities encompass mainly the ability to perform deterministic overlay and buffer operations, which are of limited use when multiple and conflicting criteria are concerned:

- Current GIS do not permit the assessment and comparison of different scenarios. They identify only solutions satisfying all criteria simultaneously.
- Analytical functionalities found in most GIS are oriented towards the management of data, not towards an effective analysis of them.
- The overlaying technique that is found in nearly all standard GIS becomes difficult to comprehend when the number of layers increases. Moreover, overlaying methods consider all features of equal importance.

The remedy suggested by some researchers is to integrate the GIS with different OR/MS tools. Practically, the idea of integrating GIS with several OR/MS tools seems to be a long-term solution. In fact, this requires the development of a coherent theory of spatial analysis parallel to a theory of spatial data (Laaribi 2000). A more realistic solution is, however, to incorporate a family of analytical methods into the GIS. Intuitively, the most suitable family is that of MCDA, which is a family of OR/MS tools that have experienced very successful applications in different domains since the 1960s. Sections 2.4 and 3.3 provide a brief description of MCDA; more information on the subject is available in the following (among others): Hwang and Yoon 1981; Vincke 1992; Pomerol and Barba-Romero 1993; Roy and Bouyssou 1993; Roy 1996; Belton and Stewart 2002.

Perhaps, the most convincing argument that supports the idea of GIS-MCDA integration is related to the complementarities of the two tools. In fact, the former is a powerful tool for managing spatially referenced data, while the latter is an efficient tool for modeling spatial problems. Another important argument (Simon 1960's) consists of the ability of MCDA to efficiently support the different phases of the decision-making process phases (i.e. intelligence, design and selection) (Chakhar and Martel 2003).

In this research, all spatial data are analyzed and processed through a GIS. The output from the GIS is different maps, with each map representing data for a number of possible alternatives for a certain criterion or vice versa. These maps are processed through different multi-criteria methods.

3.3 Multi-Criteria Decision Analysis (MCDA) techniques

In the Multi-Objective Decision Analysis (MODM) methods, the objectives are functionally related to or derived from some of the attributes. Consequently, the input data to spatial MODM problems can be stored in GIS in the form of map layers. Each map layer contains a set of objects that are considered as elements of an alternative. The alternatives are derived from the map layers by defining the relationship between the objectives and the underlying attributes of the objects contained in geographical space. Since the relationships are defined implicitly as decision variables assigned to objects, the alternatives have to be generated. The input map layers have to be processed to obtain a set of alternatives (Malczewski 1999).

In mathematical terms, MODM can be formulated as follows:

$$F(x) = \max\{f_1(x), f_2(x), \ldots, f_q(x)\}$$

subject to

$$g_v(x) \leq 0, \qquad v = 1, 2, \ldots, c, \;\; x = (x_1, x_2, \ldots, x_m)$$

where x is a vector of decision variable, $F(x)$ is the q-dimensional objective function, $f_k(x)(k=1,2,\ldots,q)$ are the objective functions, $g_v(x)$ are c distinctive constraint functions, and the constraints define the set of feasible solutions, X. In a multi-objective problem, it is desired to find a set of values for the decision variables that optimizes a set of objective functions. The set of variables that produces the optimal outcome is designated as the optimal set and denoted by x^*. Information about decision maker's preferences, which provides a rule or rules for combining the objectives or otherwise making them comparable, is required in order to find an optimal solution (Malczewski 1999). If the decision maker can only choose from a finite number of alternatives, then X is necessarily finite and the problem is discrete. If a simple decision-making problem where m alternatives are to be evaluated by n decision makers is defined, then it will use q objectives.

Table 3.1 represents the form of a conceptual decision matrix (typical objective-alternative relationships) for a MODM problem. The rows of the matrix show alternatives and the decision maker's preferences, and the columns of the matrix contain objectives. The matrix cells contain the objective functions that describe the alternatives in terms of a set of measured or assessed values of attributes with respect to the alternatives. Notice that in the MODM analysis the attributes can be organized in a GIS using the map layer structure.

3.3.1 Compromise Programming (CP)

The CP developed by Zeleny (1973) is a mathematical programming method used in MCDA problems. CP methods have been modified and improved for water resources decision-making problems because CP requires little additional input and the adjustments of only a few factors. In water resources planning the pioneer CP applications are Duckstein and Oprovic (1980) and Gershon and Duckstein (1983), and in interregional planning Hafkamp and Nijkamp (1983) are the pioneers. A very recent survey by Hayashi (2000) provides updated information about CP applications in agriculture.

The CP method can be used to identify the best compromise solution from a number of potential alternatives (Nirupama and Simonovic 2002; Zeleny 1973; Zeleny 1974). The basic idea behind CP is the identification of an ideal solution (Figure 3.1) as close as possible to the ideal point, which is possibly the only assumption made by CP about human preferences (Nirupama and Simonovic 2002). To achieve this closeness, a distance function is introduced into the analysis. The solutions identified to be closest to the ideal solution are called compromise solutions and constitute the compromise set. The compromise solution can be determined by calculating the distance of each alternative from the ideal solution and selecting the alternative with the minimum distance as the compromise solution (Goicoechea et al. 1982).

All alternatives are ranked according to their respective distance metric values. The alternative with the smallest distance metric is typically selected as the 'best compromise solution'. Equation (3.1) is the formula used to compute the distance metric values (L_j) for a set of n criteria and m alternatives.

$$L_j = \left[\sum_{i=1}^{n} w_i^p \left| \frac{f_i^* - f_{i,j}}{f_i^* - f_i^{**}} \right|^p \right]^{1/p} \tag{3.1}$$

where L_j is the distance metric, w_i is the weight of the i^{th} criteria, $f_{i,j}$ is the value of the i^{th} criteria for alternative j, f_i^* is the most optimal value of the i^{th} criteria, f_i^{**} is the least optimal value of i^{th} criteria, p is a power parameter ($1 \leq p \leq \infty$), $i = 1,...,n$ criteria, and $j = 1,...,m$ alternatives.

In Equation (3.1), each criterion is to be given a level of importance (weight), provided by the decision makers. The p - value is used to represent the importance of the maximal deviation from the ideal point. It is interesting to point out that as p increases more weight is given to the largest deviation. Thus, when $p = \infty$, the L_j distance is given exclusively by the largest deviation. In other words, the parameter p weights the deviations according to their magnitudes. It is easy to see that $p = 1$ is the largest distance and $p = \infty$ the shortest distance. It is important to note that Romero and Rehman (2003) suggest that in a strictly two-dimensional geometric sense the use of L_j metrics for values of the parameter p greater than two is meaningless, because it would mean the existence of distances shorter than the straight line.

However, as Nirupama and Simonovic (2002) proved, CP has weaknesses. The best alternative in the CP technique can be determined only for the entire geographical region. Thus, CP uses average or total impacts incurred across the entire region being considered, without accounting for spatial variation of the criteria values. The point is that without accounting for spatial variation, the criteria values may inadvertently result in a considerable amount of missing information.

Table 3-1. Matrix of the objective-alternative and objective-decision maker's preference relation for a MODM problem

	Objective *1*	Objective *2*	...	Objective *q*
Alternative *1*	f_{11}	f_{12}	...	f_{1q}
Alternative *2*	f_{21}	f_{22}	...	f_{2q}
...	...	...	...	...
Alternative *m*	f_{m1}	f_{m2}	...	f_{mq}
Decision maker's preference *1*	w_{11}	w_{12}	...	w_{1q}
Decision maker's preference *2*	w_{21}	w_{22}	...	w_{2q}
...	...	...	...	...
Decision maker's preference *n*	w_{n1}	w_{n2}	...	w_{nq}

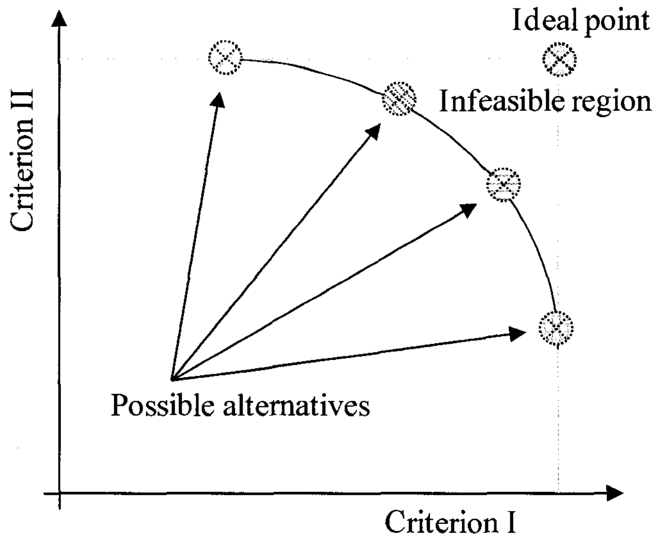


Figure 3-1. Graphical display of a simple two-criterion problem (based upon Nirupama and Simonovic (2002), modified)

3.3.2 Spatial Compromise Programming (SCP)

At the most rudimentary level, a spatial multi-criteria decision problem involves a set of geographically defined alternatives from which a choice of one or more alternatives is made with respect to given set of evaluation criteria. The alternatives are defined geographically in the sense that results of the analysis (decisions) depend on their spatial arrangement (Malczewski 1999). However, the CP method (Tkach and Simonovic 1997) has largely been aspatial. It typically uses average or total impacts incurred across the entire region being considered. To rephrase, CP assumes a spatial homogeneity within the study area. This assumption is clearly unrealistic in many decision situations because the evaluation criteria vary across space.

In contrast to the conventional MCDA, spatial multi-criteria analysis requires both data on criterion values and the geographical locations of alternatives. The data are processed using GIS and MCDA techniques to obtain information for making the decision (Malczewski 1999). Figure 3.2 shows that spatial multi-criteria decision analysis can be thought of as a process that combines and transforms geographical data into a resultant decision.

The critical aspect of spatial multi-criteria decision analysis is that it involves evaluation of geographical events based upon the criterion values and the decision maker's preferences with respect to a set of evaluation criteria. This implies that the results of the analysis depend not only on the geographical distribution of events but also on the value judgments involved in the decision-making process. Accordingly, two considerations are of critical importance for spatial multi-criteria decision analysis:

- The GIS capability for considering the unique characteristics at all points.
- The MCDA capability for considering multiple-criteria in deciding upon the spatially variable best alternatives.

The role of integrated GIS and MCDA techniques is to support the decision maker by providing greater definition and discrimination in terms of the alternatives of decision-making. Spatial Compromise Programming (SCP) (Tkach and Simonovic, 1997) was introduced to include the spatial variability in the criteria values associated with the various alternatives by combining CP with the GIS technology (Nirupama and Simonovic 2002; Tkach and Simonovic 1997).

In this approach, an individual grid cell within the feature image represents each location within the region of interest, for which a distance metric is calculated. Criteria values associated with each of the alternatives are contained within sets of criteria images, which are georeferenced with the feature images of buildings, roads, agricultural fields etc. An important point to emphasize is the fact that the spatial analysis with GIS makes possible to discriminate and determine finding whether some alternatives are better in particular areas versus others. Figure 3.3 illustrates this process graphically (Tkach and Simonovic 1997). Equation (3.1) will take the form of Equation (3.2) when the computations are carried out on a cell-by-cell basis.

$$L_{j,x,y} = \left[\sum_{i=1}^{n} w_i^p \left| \frac{f_{i,x,y}^{*} - f_{i,j,x,y}}{f_{i,x,y}^{*} - f_{i,x,y}^{**}} \right|^p \right]^{1/p} \qquad (3.2)$$

where L_j is the distance metric, w_i is the weight of the i^{th} criteria, $f_{i,j}$ is the value of the

i^{th} criteria for alternative j, f_i^* is the most optimal value of the i^{th} criteria, f_i^{**} is the least optimal value of i^{th} criteria, p is a power parameter ($1 \leq p \leq \infty$), $i = 1,...,n$ criteria, $j = 1,...,m$ alternatives, $x = 1,...,a$ rows in the image, $y = 1,...,b$ columns in the image, a is the number of rows in the image, and b is the number of columns in the image.

The traditional deterministic MCDA approach (CP and SCP) does not consider the effects of measurement error, inherent variability, instability, conceptual ambiguity, over-abstraction, or simple ignorance of important model parameters which have uncertainty, vagueness, or imprecision. Unfortunately, imprecision is inevitable in the decision-making process. Thus, it is necessary to find a new approach to reduce the effect of the imprecision on the results.

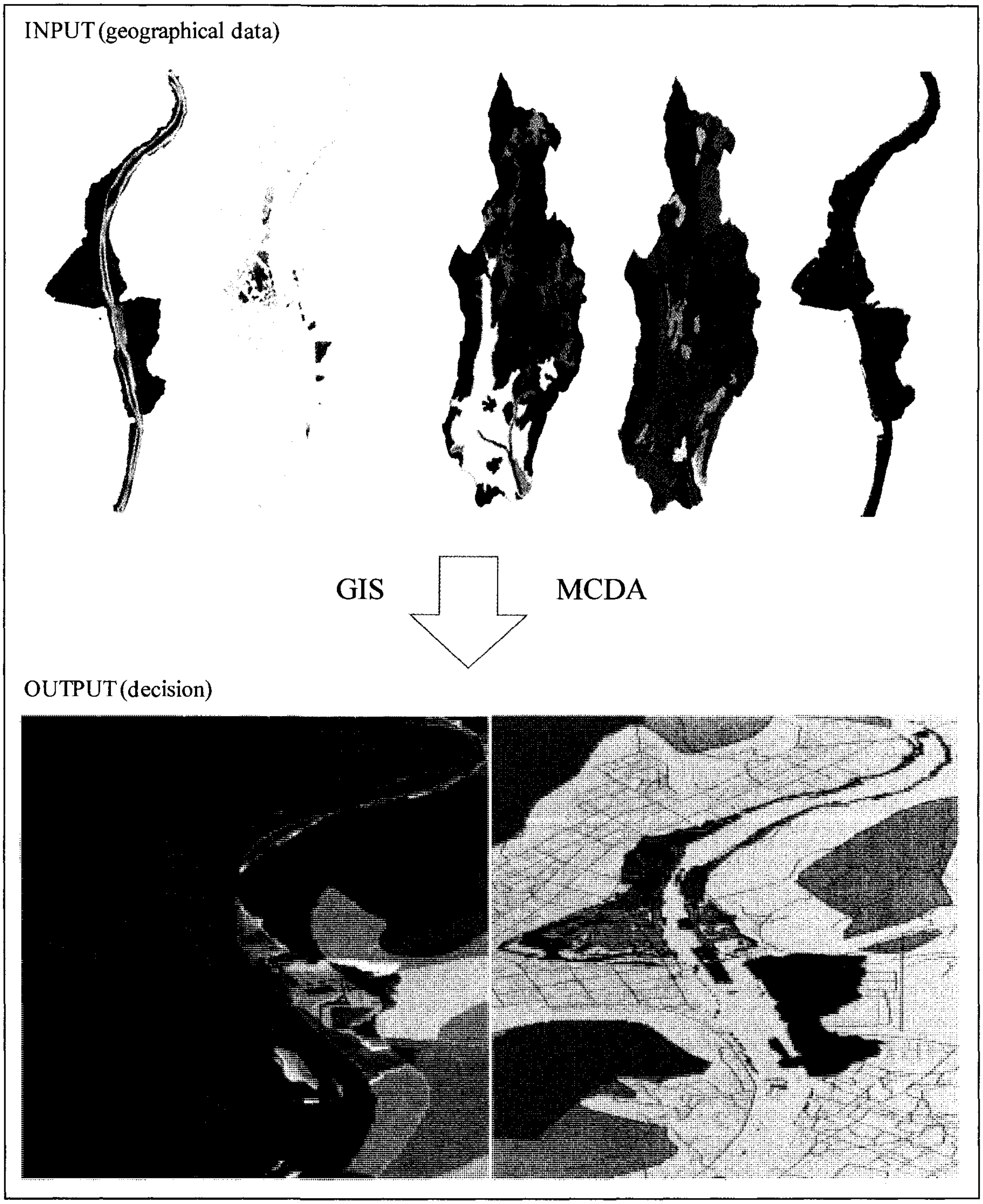


Figure 3-2. GIS-based spatial fuzzy multi-criteria decision analysis example: input-output perspective

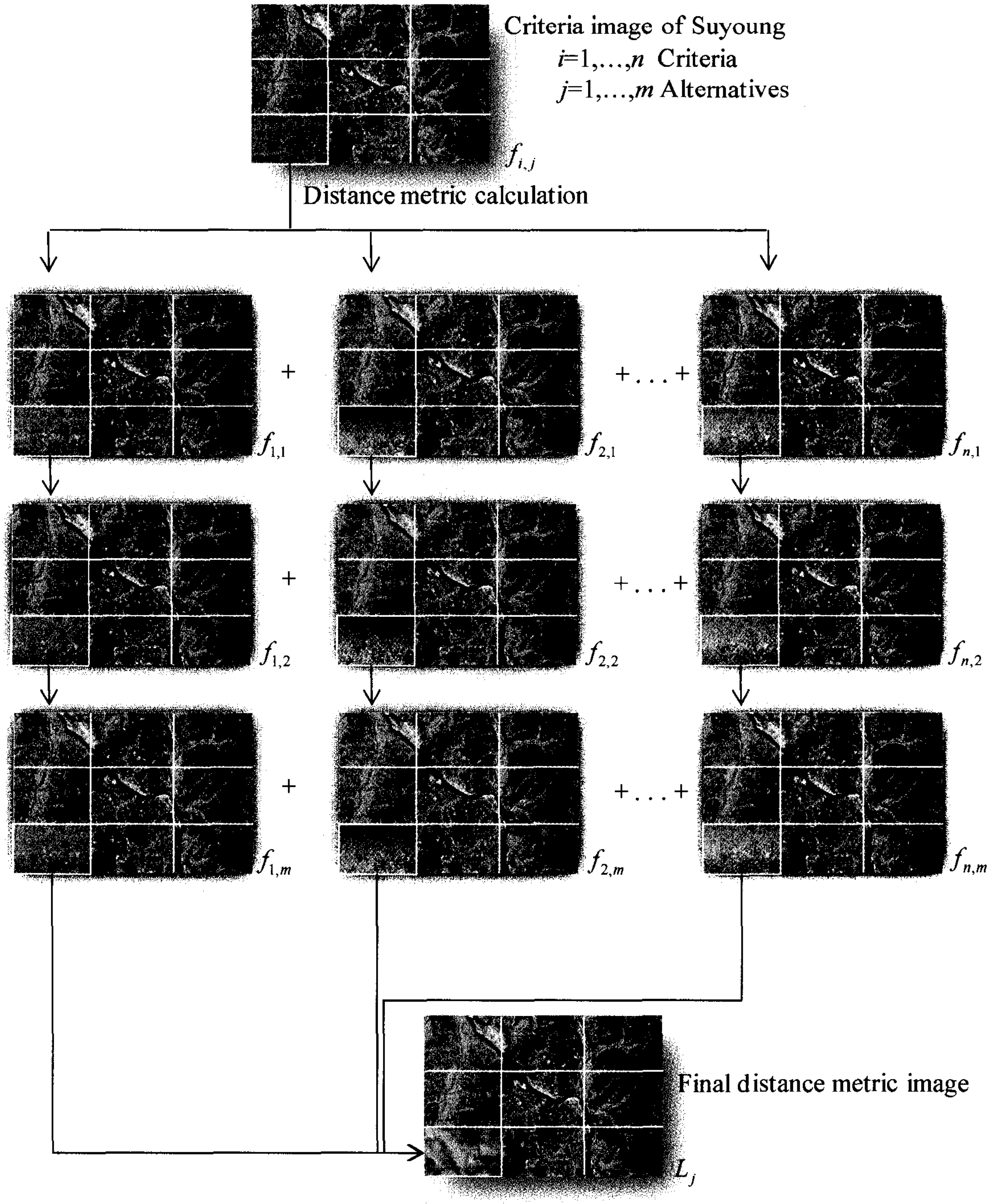


Figure 3-3. Cell by cell calculation of distance metric values (based upon Nirupama and Simonovic (2002), modified)

3.3.3 Spatial Fuzzy Weighted Average Method (SFWAM)

Information must be synthesized whenever decision-making is employed in an MCDA system, in order to lessen imprecision and resolve the ambiguity often present in the information from a data set. The SCP method, however, is unable to address the effect of imprecision on the answers in model parameters, criteria values, equipment accuracy, or lack of knowledge that also contribute to complexity in the decision-making process. Since these inputs to the MCDA are imprecise in nature, new methods are needed such that this imprecision can be represented and managed appropriately (Vanegas and Labib 2001). Several approaches for imprecision characterization by vagueness, inexactness, and ill definition have been proposed in the literature. Alternative ways of decreasing imprecision such as probability theory, neural networks and fuzzy set theory are needed (Lee and Park 1997). Among them, fuzzy set theory has emerged as a powerful way of quantitatively representing and manipulating the imprecision in decision-making problems in a great variety of applications after Dong and Wong (1987) proposed an algorithm to compute the fuzzy weighted average based upon the extension principle.

Fuzzy set theory can appropriately represent imprecise parameters, and can be manipulated through different operations on fuzzy numbers. Since vague parameters and weighting sets are treated as imprecise values instead of precise ones, the process will be more powerful and its results will have more credibility (Vanegas and Labib 2001). For example, according to Bender and Simonovic (2000) many criteria in floodplain management problems are subjective in nature, so using fuzzy set theory seems appropriate. Because both importance levels of criteria as well as performance of alternative candidate data per criterion are usually vague, fuzzy numbers are able to handle subjective imprecision rather well. These, in some cases, may be associated with numeric terms; for example, preferences of a decision maker can be described by numeric terms, such as the crisp value 0.5 can be converted to a range of 0.25 to 0.75 while keeping its own value 0.5. This is a fairly convenient way of fuzzifying any number (Nirupama and Simonovic 2002; Vanegas and Labib 2001).

The Spatial Fuzzy Weighted Average Method (SFWAM) is an MCDA technique designed to incorporate various sources of imprecision. These imprecision may come from the natural hydrological processes, the measurement of the data and the imprecision of the decision maker preferences (Nirupama and Simonovic 2002). This approach was developed by Bender and Simonovic (2000).

The transformation of a distance metric to a fuzzy set can be accomplished by changing all inputs from crisp to fuzzy and applying the fuzzy extension principle (Nirupama and Simonovic 2002).

$$\tilde{L}_j = \left[\sum_{i=1}^{n} \tilde{w}_i \left| \frac{\tilde{f}^{*}_{i,x,y} - \tilde{f}_{i,j,x,y}}{\tilde{f}^{*}_{i,x,y} - \tilde{f}^{**}_{i,x,y}} \right| \right] \tag{3.3}$$

where $\tilde{L}_j$ is the fuzzy distance metric, $\tilde{w}_i$ is fuzzified weight of i^{th} criteria, $\tilde{f}_{i,j}$ is the fuzzy value of the i^{th} criteria for alternative $_c$, $\tilde{f}^{*}_i$ is the fuzzy most optimal value of the i^{th} criteria, $\tilde{f}^{**}_i$ is the fuzzy least optimal value of i^{th} criteria, $i = 1,...,n$ criteria, and $j = 1,...,m$ alternatives.

In Equation (3.3), weights can be fuzzified to account for indecisiveness of their boundary values, for an instance, a value of 0.5 could be defined as approximately 0.5 (0.25 ~ 0.75). This means that fuzzy boundaries of weight values will take care of the imprecision associated with crispness. Expressing possibility values with fuzzy inputs allows experience to play a significant role in the expression of input information. The shape of a fuzzy membership function expresses the experience or the interpretation of a decision maker. The best alternative for each location is determined by comparing the values in the distance metric images for each individual grid cell between the alternatives.

3.3.4 Improved Spatial Fuzzy Weighted Average Method (ISFWAM)

Considering the literature available on MCDA techniques, it was realized that there is a need to develop a methodology that combines the three important issues, since time and space play an important role in flood management. Specifically, these are the GIS capabilities for finding more spatially distributed strategies, the MCDA capabilities for considering multiple-criteria in deciding on best alternatives, and the fuzzy capabilities for lessening the effect of the imprecision on the answer.

The ISFWAM was introduced to include these three objectives. ISFWAM works on the same principle as that of SFWAM with the addition of considering the fuzzified parameter p value. Fuzzy theory offers a way to represent and improve the consideration of imprecision. For example, rather than saying that is better or worse in the analysis it is important to note that spatial analysis and consideration of imprecision actually gives the decision maker a greater diversity of the answers. It is possible to show greater diversity and greater spatial distribution of the best alternatives. This fuzzification has been proposed to account for the vagueness in the entire process of decision-making. The process of cell-by-cell fuzzification of each input image can be carried out using appropriate membership functions, such as gaussian, triangular-shaped, sigmoidally shaped, S-shaped or Z-shaped. Modification of Equation (3.3) with inclusion of fuzzy inputs will give the distance metric formula for ISFWAM as shown in Equation (3.4). It should be noted that imprecision associated with the simulation of natural hydrologic processes that are being represented and the imprecision arising from the data used along with the accuracy of equipment used to collect the data can be satisfactorily addressed through probabilistic approaches. The lack of knowledge that brings in some vagueness can be address with the help of fuzzy theory. Therefore, some of the inputs could remain in deterministic form provided the level of confidence about their accuracy is satisfactorily high, while others can remain fuzzy. In this way a combination of fuzzy and deterministic inputs can also be handled by an ISFWAM approach (Nirupama and Simonovic 2002).

Fuzzy distance-based techniques measure the distance from an ideal point, where the ideal alternative would result in a distance metric $\tilde{L}:\tilde{X}\rightarrow\{0\}$. Hence, alternatives, which tend to be closest to the ideal solution will be selected.

$$\tilde{L}_{j,x,y}=\left[\sum_{i=1}^{n}\tilde{w}_i^{\tilde{p}}\left|\frac{\tilde{f}^{*}_{i,x,y}-\tilde{f}_{i,j,x,y}}{\tilde{f}^{*}_{i,x,y}-\tilde{f}^{**}_{i,x,y}}\right|^{\tilde{p}}\right]^{1/\tilde{p}} \tag{3.4}$$

where $\tilde{L}_{j,x,y}$ is the fuzzy distance metric, $\tilde{w}_i$ is fuzzified weight of i^{th} criteria, $\tilde{f}_{i,j,x,y}$ is the fuzzy value of the i^{th} criteria for alternative j, $\tilde{f}^{*}_{i,x,y}$ is the fuzzy most optimal value of the i^{th} criteria, $\tilde{f}^{**}_{i,x,y}$ is the fuzzy least optimal value of i^{th} criteria, $\tilde{p}$ is a fuzzified power parameter ($1\le p\le\infty$), $i=1,...,n$ criteria, $j=1,...,m$ alternatives, $x=1,...,a$ rows in the image, $y=1,...,b$ columns in the image, a is the number of rows in the image, and

b is the number of columns in the image.

As we noted a little earlier in this chapter, p is likely the most uncertain element of distance metric computation. There is no single acceptable value of p for every problem and it is not related to problem information. Fuzzification of the distance metric exponent, p, can take many forms but in a practical way, it might be defined by an S-shaped fuzzy set with a mode of 2. As illustrated in Figure 3.4, the fuzzified distance metric values within the images are calculated by comparing impacts for each location on a cell by cell basis between all alternatives and applying the decision makers' preferences, which are in fuzzy form as well (Nirupama and Simonovic 2002).

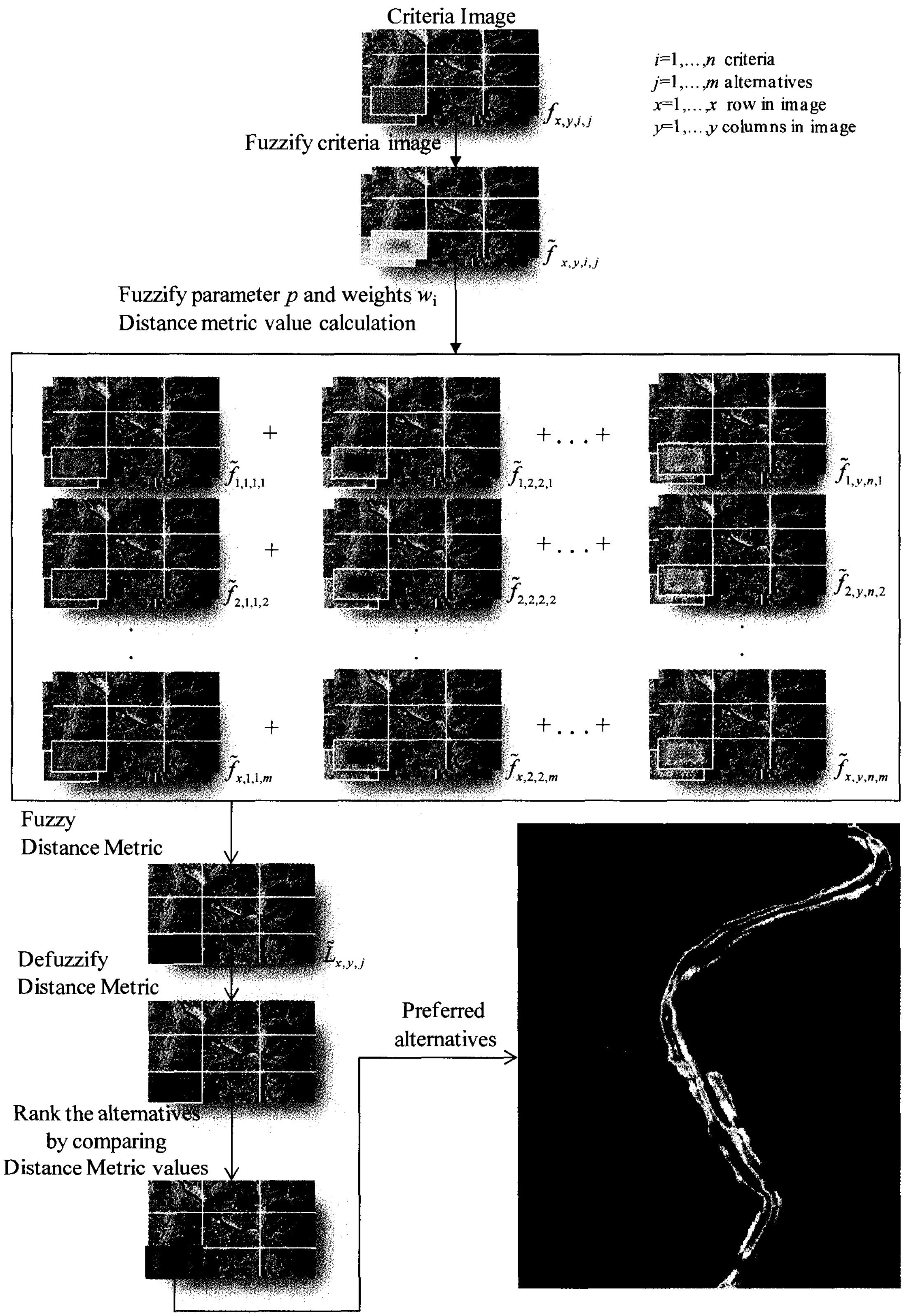


Figure 3-4. ISFWAM procedure for ranking of flood damage reduction alternatives (based upon Nirupama and Simonovic (2002), modified)

3.4 Fuzzy set theory

3.4.1 Fuzzy sets and fuzzy numbers

Fuzzy sets, to treat fuzziness in data, are an extension of classical set theory and are used in fuzzy logic. Professor Lofti Zadeh at the University of California formalized fuzzy set theory in 1965. What Zadeh proposed is very much a paradigm shift that first gained acceptance in the Far East and its successful application has ensured its adoption around the world. A paradigm is a set of rules and regulations which defines boundaries and tells us what to do to be successful in solving problems within these boundaries (Aziz and Parthiban 2007).

In classical set theory the membership of elements in relation to a set is assessed in binary terms according to a crisp condition - an element either belongs or does not belong to the set. Classical set theory can be somewhat limiting if one wish to describe a humanistic problem mathematically. By contrast, fuzzy set theory permits the gradual assessment of the membership of elements in relation to a set; this is described with the aid of a membership function $\mu = [0,1]$. Fuzzy sets are an extension of classical set theory since, for a certain universe, the membership grade can be taken as a value intermediate between 0 and 1 although in the normal case of set theory membership the grade can be taken only as 0 or 1. Figure 3.5 shows a comparison between the normal case of set theory and fuzzy set theory. The function of the membership grade is called its "membership function" in fuzzy theory. The membership function will be defined by the user in consideration of the fuzziness. The universe of discourse is the range of all possible values for an input to a fuzzy system.

Specifically, a fuzzy set on a classical set X is defined as follows: The membership function $\mu_A(x)$ quantifies the grade of membership of the elements x to the fundamental set X. An element mapping to the value 0 means that the member is not included in the given set, whereas 1 describes a fully included member. Values strictly between 0 and 1 characterize the fuzzy members. The following holds for the functional values of the membership function $\mu_A(x)$.

$$\mu_A(x) \geq 0 \qquad \forall x \in X \qquad \sup_{x \in X}\left[\mu_A(x)\right] = 1 \tag{3.5}$$

3.4.2 Fuzzy set operations

A fuzzy set operations are generalizations of crisp set operations. There is more than one possible generalization. The most widely used operations are called standard fuzzy set operations (http://en.wikipedia.org/wiki/Fuzzy_set_Operations). There are three operations: fuzzy union, fuzzy intersection, and fuzzy complement (Aziz and Parthiban 2007).

Union: The membership function of the union of two fuzzy sets A and B with membership functions μ_A and μ_B respectively is defined as the maximum of the two individual membership functions (Figure 3.6). This is called the *maximum* criterion. The union operation in fuzzy set theory is the equivalent of the OR operation in Boolean algebra.

$$\mu_{A \cup B} = \max\left(\mu_A, \mu_B\right) \tag{3.6}$$

Intersection: The membership function of the intersection of two fuzzy sets A and B with membership functions μ_A and μ_B respectively is defined as the minimum of the two individual membership functions (Figure 3.6). This is called the *minimum* criterion.

The intersection operation in fuzzy set theory is the equivalent of the AND operation in Boolean algebra.

$$\mu_{A \cap B} = \min(\mu_A, \mu_B) \tag{3.7}$$

Complement: The membership function of the complement of a fuzzy set A with membership function μ_A is defined as the negation of the specified membership function. This is called the *negation* criterion. The complement operation in fuzzy set theory is the equivalent of the NOT operation in Boolean algebra.

$$\mu_{\bar{A}} = 1 - \mu_A \tag{3.8}$$

The following rules, common in classical set theory, also apply to fuzzy set theory.

De Morgans law: $\left(\overline{A \cap B}\right) = \bar{A} \cap \bar{B},\ \left(\overline{A \cup B}\right) = \bar{A} \cup \bar{B}$ (3.9)

Associativity: $\begin{array}{l}(A \cap B) \cap C = A \cap (B \cap C) \\ (A \cup B) \cup C = A \cup (B \cup C)\end{array}$ (3.10)

Commutativity: $A \cap B = B \cap A,\ A \cup B = B \cup A$ (3.11)

Distributivity: $\begin{array}{l}A \cap (B \cup C) = (A \cap B) \cup (A \cap C) \\ A \cup (B \cap C) = (A \cup B) \cap (A \cup C)\end{array}$ (3.12)

Fuzzy set theory provides a rich mathematical basis for understanding decision problems and for constructing decision rules in criteria evaluation and combination (Eastman 2003). There exist numerous types of membership functions, the most commonly used in practice are triangles, trapezoids, bell curves, gaussian, and sigmoidal functions. Two types of membership function will be introduced below.

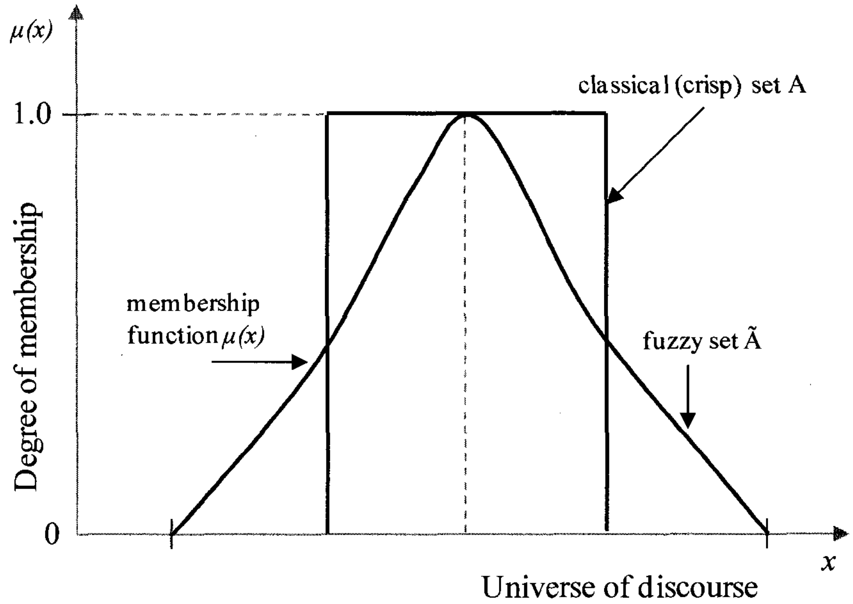
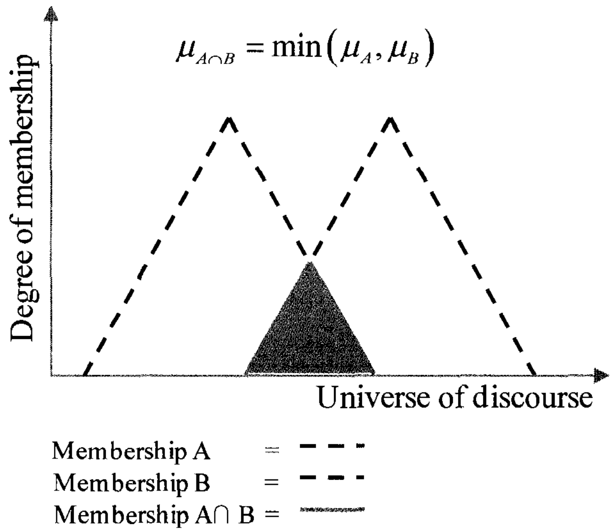


Figure 3-5. Fuzzy set and crisp set



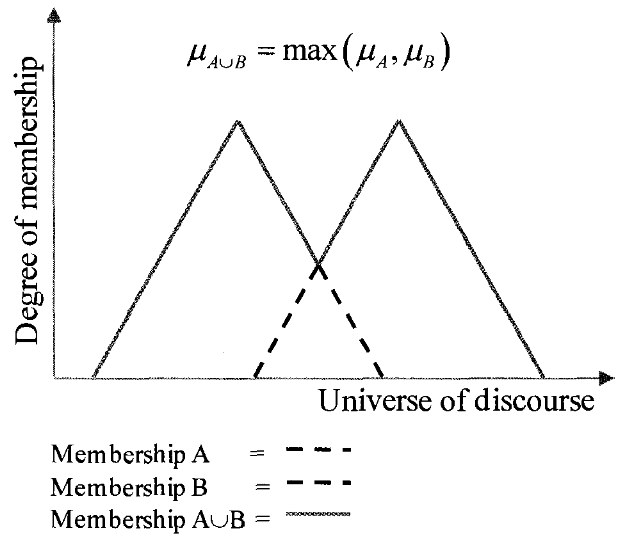


Figure 3-6. Union and intersection of two fuzzy set

1) Triangular Membership Function (TMF): a triangular membership function is specified by three parameters $\{a,b,c\}$ as follows:

$$T(x:a,b,c)=\begin{cases} 0 & x<a \\ \dfrac{x-a}{b-a} & a\leq x\leq b \\ \dfrac{c-x}{c-b} & b\leq x\leq c \\ 0 & x>c \end{cases} \tag{3.13}$$

The precise appearance of the function is determined by the choice of parameters *a*, *b*, and *c*. The choice of triangular membership has been made due to its characteristic that this function expands a crisp value on both sides of the crisp value to convert the crisp value into a range format. For example, a crisp value of 4 can be converted to a range of 3.5 to 4.5 while keeping the value 4 as the peak value. This is a fairly convenient way of fuzzifying any number (Nirupama and Simonovic 2002).

2) S-shaped Membership Function (SMF): the S-shaped membership function is a smooth membership function with two parameters: *a* and *b*. the shape of the function is shown in Figure 3.7. The membership value is 0 for points below *a*, 1 for points above *b*, and 0.5 for the midpoint between *a* and *b*. The name of this type of membership function comes from the S-shaped of the function (Yen and Langari 1999). SMF takes any crisp value *x* and expands it according to the shape of the membership function. The fuzzified value is always in the form of an increasing function (maintaining the S-shaped) between one and zero. For the particular application in this study, S-shaped MF is appropriate

because of its shape, which varies from the highest MF value (one) to the lowest MF value (zero). This shape is suitable to both the criteria considered in this study, namely flood water depth and damage, because when flood water depth is minimum (zero on x-axis) then the degree of membership is lowest (zero on y-axis) and vice-versa. Similarly, maximum damage provides highest degree of membership, which suits the particular objective in this research of minimizing flood damages (Nirupama and Simonovic 2002).

$$S(x:a,b)=\begin{cases} 0 & x<a \\ \left(\dfrac{x-a}{b-a}\right)^2 & a\le x\le \dfrac{a+b}{2} \\ 1-2\left(\dfrac{x-b}{b-a}\right)^2 & \dfrac{a+b}{2}\le x<b \\ 1 & x\ge b \end{cases} \tag{3.14}$$

3.4.3 Fuzzy arithmetic

Fuzzy arithmetic has been defined to manipulate fuzzy numbers. These operations may be based upon the extension principle, or on the arithmetic of operations on intervals and the fact that any fuzzy number can be completely defined by its family of α-cuts (section 3.4.4). The extended algebraic operations are defined by Klir and Yuan (1995), based upon arithmetic on intervals and assuming that fuzzy numbers are represented by continuous membership functions. The fuzzy set obtained by an arithmetic operation on the fuzzy numbers A and B, on $\mathbb{R}$, is defined by its α-cuts as follows:

Addition $\quad (A\oplus B)_\alpha = A_\alpha + B_\alpha \quad$ (3.15)

Subtraction $\quad (A-B)_\alpha = A_\alpha - B_\alpha \quad$ (3.16)

Multiplication $(A \otimes B)_\alpha = A_\alpha \cdot B_\alpha$

$$\textit{and provided that } 0 \notin B_\alpha \textit{ for all } \alpha \in (0,1) \tag{3.17}$$

Division $$(A \varnothing B)_\alpha = A_\alpha / B_\alpha \tag{3.18}$$

for any $\alpha \in (0,1)$, where $(A * B)_\alpha$ (* is any of the four arithmetic operations $\oplus, -, \otimes, \varnothing$) is a crisp set (interval) that represents the α-cut of the fuzzy set obtained by operating on the fuzzy numbers A and B; A_α and B_α represent the α-cuts of the fuzzy numbers A and B respectively. The family of α-cuts $(A * B)_\alpha$ that is obtained through an arithmetic operation defines a new fuzzy set, which also classifies as a fuzzy number. An arithmetic operation on the *fuzzy numbers A* and *B* is therefore reduced to operations on the *intervals* A_α and B_α. The five arithmetic operations on closed intervals are defined below (Klir and Yuan 1995). For any two intervals, $[a,b]$ and $[d,e]$, the arithmetic operations are performed in the following way:

$$[a,b] + [d,e] = [a+d, b+e], \tag{3.19}$$

$$[a,b] - [d,e] = [a-e, b-d], \tag{3.20}$$

$$[a,b] \cdot [d,e] = \left[\min[ad, ae, bd, be], \max[ad, ae, bd, be]\right],$$
$$\textit{and, provided that } 0 \notin [d,e], \tag{3.21}$$

$$[a,b]^{[d,e]} = \left[\min\left[a^d, a^e, b^d, b^e\right], \max\left[a^d, a^e, b^d, b^e\right]\right], \tag{3.22}$$

$$[a,b]/[d,e] = [a,b] \cdot \left[\frac{1}{e}, \frac{1}{d}\right] = \left[\min\left[\frac{a}{d}, \frac{a}{e}, \frac{b}{d}, \frac{b}{e}\right], \max\left[\frac{a}{d}, \frac{a}{e}, \frac{b}{d}, \frac{b}{e}\right]\right]. \tag{3.23}$$

3.4.4 Alpha-cuts

The concept of an α -cut of a fuzzy set is useful for defining the arithmetic operations on fuzzy numbers. The α -cuts of a fuzzy set A is the (crisp) set A_α of elements x, such that their degree of membership in the set A is at least equal to $\alpha\left(0 \leq \alpha \leq 1\right)$ (Klir and Yuan 1995). The α -cut is then expressed by:

$$A_\alpha = \left\{x \in X \mid \mu_A\left(x\right) \geq \alpha\right\} \tag{3.24}$$

Figure 3.8 illustrates this concept. The α -cut (α =0.4) of the fuzzy set represented by the membership function in Figure 3.8 is the (crisp) interval of real numbers [2, 4]. Note that all the numbers in this interval have a degree of membership greater than or equal to α =0.4 (Vanegas and Labib 2001).

3.4.5 Defuzzification and ranking

Typically, a fuzzy system will have a number of rules that transform a number of variables into a fuzzy result, that is, the result is described in terms of membership in fuzzy sets. However, for most applications there is a need for a single action or crisp solution to emanate from the inference process. This will involve the 'defuzzification' of the solution set. Defuzzification is the process of converting the fuzzified distance metric to a quantifiable crisp value that best represents a fuzzy set. In this study defuzzification has been carried out on a cell by cell basis to get the defuzzified value out of fuzzified distance metric values for the entire region of interest (Nirupama and Simonovic 2002). There are various defuzzification techniques available in the literature such as the max criterion, mean of maximum, bisector of area, smallest of maximum, largest of maximum and the center of area method. The max criterion method finds the point at which the membership function is a maximum. The mean of maximum takes the mean of those points where the membership function is at a maximum. The most common method is the center of area method which finds the center of gravity of the solution fuzzy sets (Nirupama and Simonovic 2002).

The last step involves ranking the alternatives. This can be accomplished simply by representing the alternatives in terms of fuzzy numbers derived from the final maps obtained in the defuzzification step. The alternatives are characterized by the cells in a raster image (Malczewski 1999). By ranking cells and then reclassifying the result, a specific number of the best or worst ranks can be determined. (Eastman 2003).

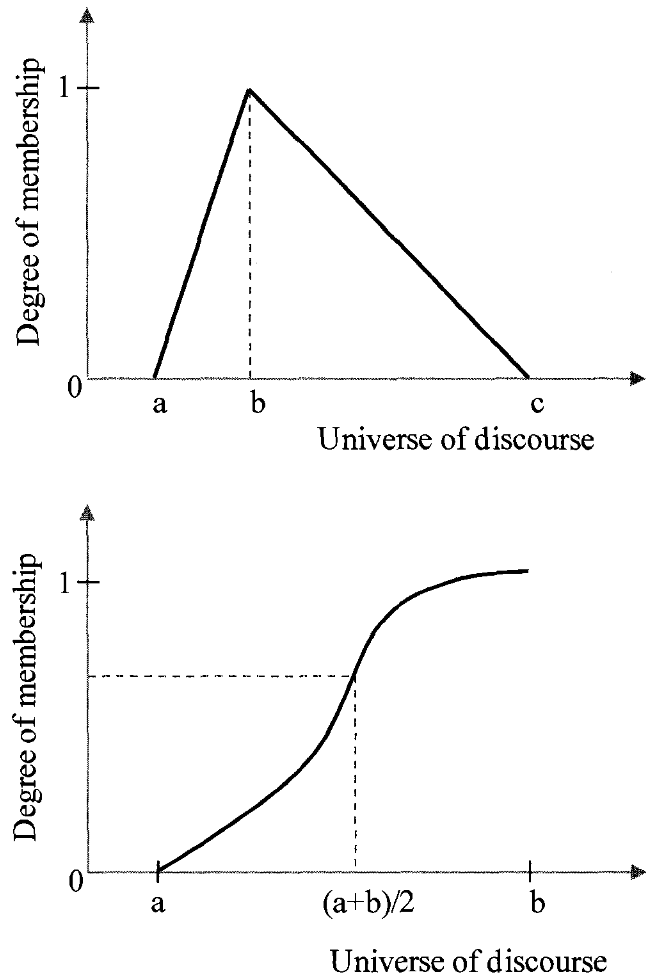


Figure 3-7. Triangular and s-shaped membership function

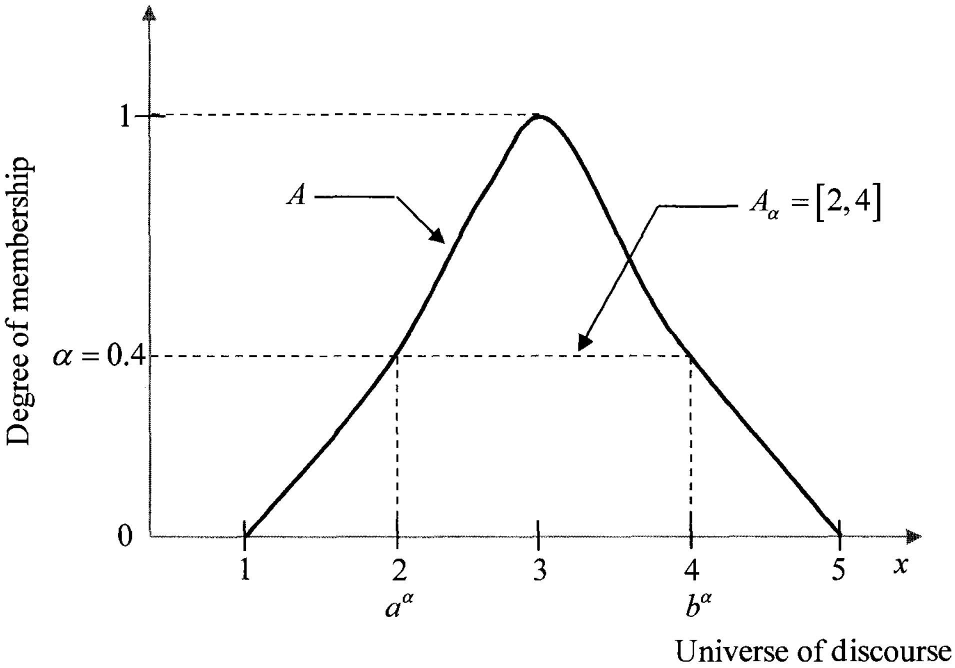


Figure 3-8. Example of the α-cut of set A for α =0.4

CHAPTER 4: CASE STUDY

4.1 Introduction

This chapter describes an implementation and validation of the developed general methodology for evaluating flood damage reduction alternatives in the Suyoung River Basin of Korea. The purpose of the case study is to demonstrate how the developed model might be applied to a specific river basin for flood management purpose. The full procedure is shown in more detail in Figure 1.1.

This case study will focus on the following points:

1) Advantages of the use of an adjusted DEM as a base map for MCDA
2) Implementation and comparison of deterministic and spatial fuzzy MCDA
3) Benefits of a GUI based MCDA GIS-based interactive model
4) Testing whether more criteria produce more or less diversity of preferred options

The rest of this chapter is organized as follows: Section 2 explains the experimental setup including physical and hydrological characteristics of the basin, identification of candidate criteria, defining flood damage reduction alternatives, and finally hydraulic and hydrologic data development. Section 3 details the approach of the research with respect to integrating the low-resolution DEM with existing surveyed channel elevation data. The results of the simulated flood inundation map will be compared with actual 1991 Gradys flood map data. In section 4 ("A GIS-based MCDA interactive model"), computer program coding will be described. Sections 5 and 6 offers an explanation of the deterministic and spatial fuzzy MCDA approaches. The last section of this chapter (section 7) will summarize and discuss the results.

4.2 Experimental design

4.2.1 Suyoung River Basin (physical and hydrological characteristics)

The Suyoung basin in Pusan Province, located on the southeastern tip of Korea was chosen as a case study; Pusan is the largest trading port in Korea and a central city in the Pacific Rim trade (shown in Figure 4.1). The entire study area covers an area of 199.65 km^2 and the population of this area is about 4 million people. The Suyoung River is the main stream that flows through the area. The major reasons for flooding in the Suyoung River are typhoons and depression torrential storms. Moreover, this area has no facilities to release flood water. Relatively short river reaches and steep channel slopes also contribute to frequent flood disasters. A typical typhoon storm case in the Suyoung basin is the 1991 Gladys flood event, during which rainfall occurred continuously for several days. The main cause of flood damage was the excessive rise in the water level of the Suyoung River. The highest water level was recorded at 10.6*m* which is 1.1*m* higher than the flood hazard water level. Levees were washed away and about 13,807*ha* of farmlands were inundated. The estimated total property loss was about 7.5*million* US$ (MOCT & KOWACO, 2001).

For the application of the developed methodology for evaluating flood damage reduction alternatives, the 1991 flood event and five different return periods were selected. Figure 4.2 shows the road network and distribution of buildings, and hence the urbanization in Suyoung. Approximately 21,813 buildings were integrated into a vector ArcGIS spatial database. This included attribute information such as the type of building.

4.2.2 Identifying candidate criteria for evaluating flood protection alternatives

The determination of which criteria should be adopted for the study of evaluating flood damage reduction alternatives in the Suyoung area depends on studies of the acceptability and ease of data collection, reliability of the collected data, as well as the decision-making model and its structure. Gomes and Lins (2002) insist that for the decisions to be based upon valid data, it is necessary to think about what can be measured and how these data will be used. In this case study, the criteria were chosen on the basis of the existence and ease of obtaining the data for the Suyoung River Basin. They were also selected to provide more discrimination in terms of the preferred alternatives for a specific spatial location. Figure 4.3 displays the decision criteria for this structuring problem.

Each one of the criteria used to evaluate the performance of the potential alternatives has an important role in the decision-making process. These criteria should be reasonably independent. The evaluation candidate alternatives are measured with five criteria for which the data exhibit a spatial variability and need the integration of mathematical procedures in order to make images of criteria maps. These criteria are: (1) Flood water depth, (2) flood damage, (3) land use disruptions, (4) risk of flooding under different return periods, and (5) drainage capacity.

The first criterion used in the evaluation of the alternatives is the flood water depth for the Suyoung River Area. This criterion map predicts where the water would flow over

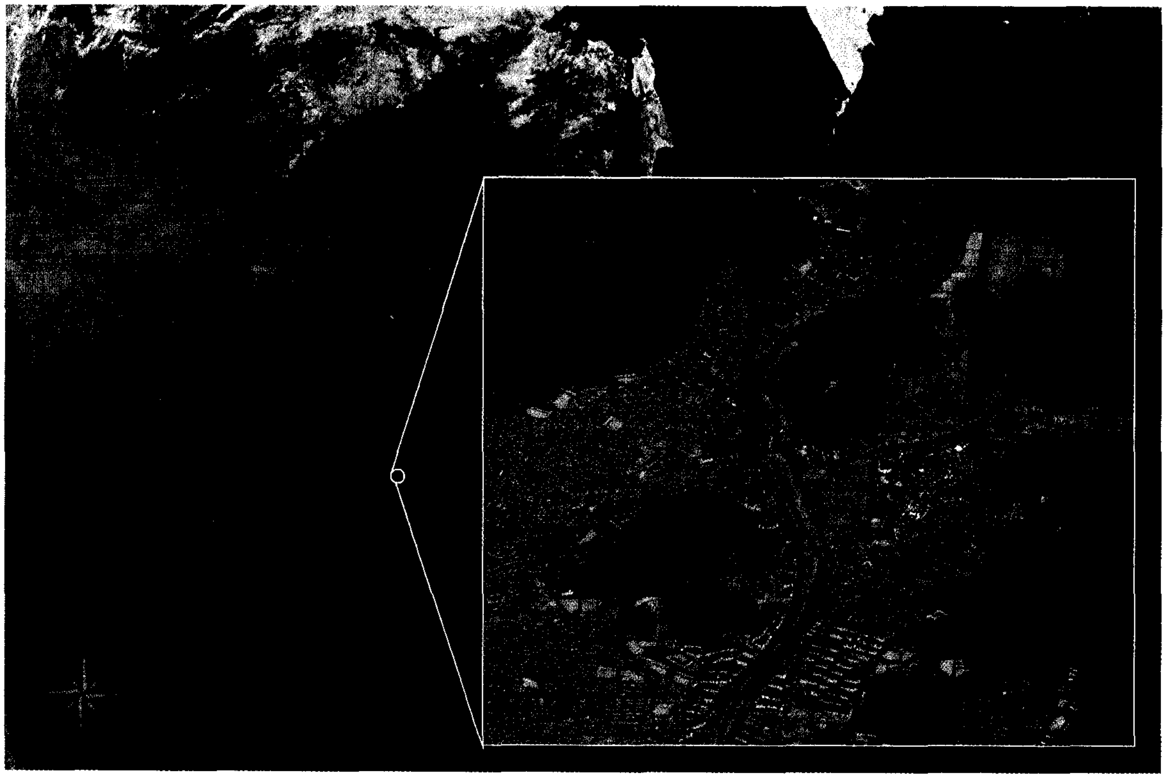


Figure 4-1. Map showing the study region (The Suyoung River in Korea)

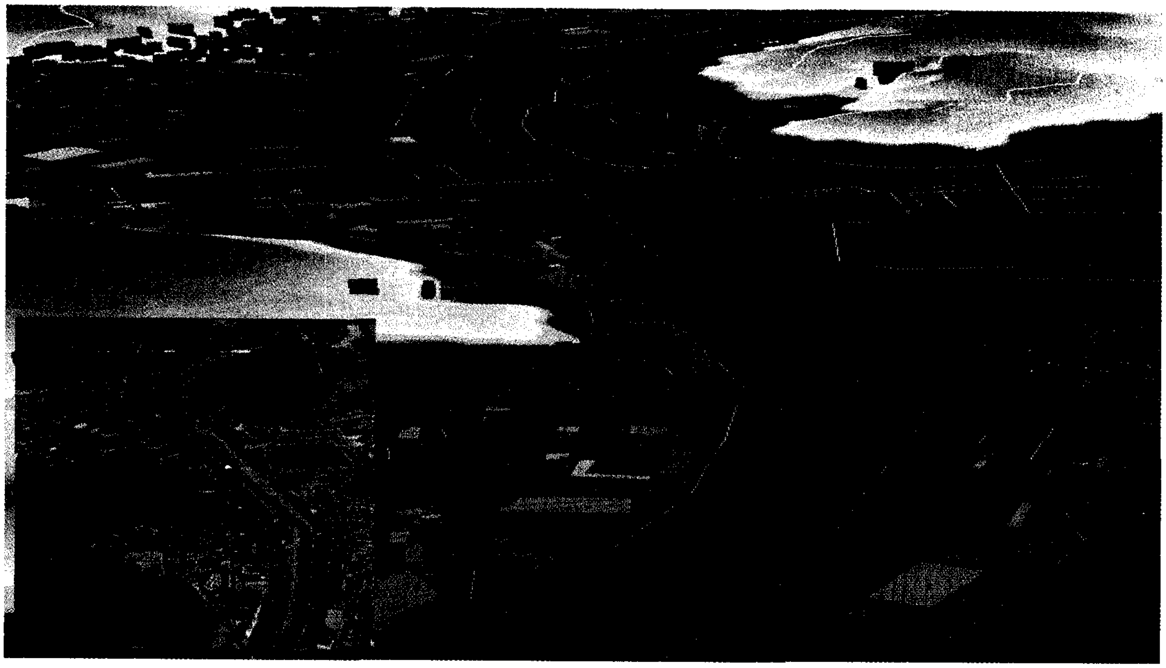


Figure 4-2. Suyoung city looking north (visualization based on 20*m* grid resolution DEM showing relief and road network)

time and how deep it is likely to get, given various return periods. An image of this criteria was prepared in which each grid cell contains the water depth. The DEM representing the land terrain elevation was subtracted from the water surface DEM, yielding positive values where the flood elevation is numerically greater than the land elevation (inundation) and negative values elsewhere (Jones et al. 2001). A zero or negative value location means that location was unaffected by the given floodwaters. Each of the previously mentioned alternatives has its own set of water depth values covering the entire inundated area. According to the MCDA equation mentioned in section 3.3, the best and the worst criteria values of each of criteria map are required. To find the best and worst criteria values, the minimum flood water depth and the maximum flood water depth are considered respectively. Table 4.4 indicates the best and worst values for the flood water depth criterion.

The second criterion is flood damage. Queensland (2002) commented that the relationship between the level of inundation by flood water and the resulting damage to buildings is influenced by the flooded depth of the buildings. Floodplain mapping predicts the extent and depth of flood water for varying levels of flood severity. These flood maps provide information regarding the locations of affected buildings, ground levels, and flood levels, all of which are required to calculate a damage estimate for buildings and roads. These maps will be described in section 4.3. To use submerged area-damage curves in this step, an estimate must be made of the height of inundation (above floor level) at each of the affected properties. Thus, an image in which each raster cell contains the water depth was multiplied with each building and road image value using the raster calculator function of the ArcGIS software. Final raster cell values indicate the height of inundation. Note that in this study, the flood damage was estimated on a grid base of $3m$ by $3m$ and $5m$ by $5m$. The submerged area-damage curves provided by MOCT (2001) are separated into metropolis, small town, suburbs, rural area, and forest area (Table 4.1). Small town was picked for the Suyoung River Basin in this research because of its size. Four damage type curves have been developed to cover the range of damage types (building, agriculture, public facility, etc). Then household damage rates per flooding depth used for flood damage were applied to each final raster cell (Table 4.2). The total damage cost was calculated by summing of the individual building and road damages.

The third criterion is the land use disruption of the study area. Land use characteristics affect floods. Forested and heavily vegetated drainage basins generally produce floods of smaller peaks and longer durations than comparable bare basins. Urban and suburban developments can have profound effects on flooding. For this reason, land use will be employed as a different criterion from the flood damage. As an example, if the flooded areas contain structures that may have a high population of people like housing, industrial buildings, or hospitals, they will have higher avoidance values than farmland. The land use disruption criterion also takes into account areas such as highways where disruption or interruption of service due to flooding would be particularly troublesome. This type of rating scale should be selected to fit the decision maker's desires and the characteristics of the flooding problem. A scale of 1 to 100, with 100 representing the greatest susceptibility to flood damage and 1 representing the least susceptibility to flood damage, was selected for this criterion.

The fourth criterion is the risk of flooding under different return periods. This criterion varies with different kinds of flood damage reduction alternatives. It is divided into six categories, Zone 1 through Zone 6. Zone 1 represents the area that is likely to flood with a 10-yr design flood. A Zone 2 area will be submerged by a 20-yr design flood but not by a 10-yr flood (Zone 2 area = 20-yr inundation area – 10-yr inundation area). Similarly, in Zone 5 there is no flood damage for 10-yr, 20-yr, 50-yr, or 100-yr floods, but only for 200-yr floods. However, there is no flood damage in Zone 6 for any design flood event. The rating scale is shown in Table 4.3.

The last criterion is the drainage capacity. Different types of soil have different capacities for retaining rainwater. If the soil in an area will not hold enough rainwater, flooding problems will ensue. For that reason, drainage capacity was chosen as the last criterion. The drainage capacity rating scale comes from the simple question: "Which type of soil would be most likely to cause flooding problems?" The final criterion scale ranges from 20 to 100, with 100 representing the least drainage performance, and 20 representing the best drainage performance. Each raster cell contains a rating value (Table 4.3) for all distinct geographic locations, after converting drainage capacity type to a proper rating scale. The rating scale is shown in Table 4.3.

Table 4-1. Submerged area-damage relationships for each area type (Unit: million, *ha*)

Area type	Type	Constant	Submerged area term	Fitness
Metropolis	Building	0.23294	$0.245\,S^2$	0.63
	Agriculture	0.09896	$0.288\,S^2$	0.91
	Public facility	0.53365	$0.149\,S^2$	0.55
	Etc	0.03835	$1.741\,S^2$	0.44
[redacted]				
Suburbs	Building	0.13849	$0.302\,S^2$	0.78
	Agriculture	0.00528	$0.353\,S^2$	0.80
	Public facility	0.38754	$0.215\,S^2$	0.51
	Etc	0.11562	$0.310\,S^2$	0.64
Rural Area	Building	0.01164	$0.286\,S^2$	0.95
	Agriculture	0.11744	$0.226\,S^2$	0.84
	Public facility	0.38670	$0.157\,S^2$	0.63
	Etc	0.49185	$0.130\,S^2$	0.62
Forest Area	Building	0.41041	$0.271\,S^2$	0.72
	Agriculture	0.64000	$0.165\,S^2$	0.65
	Public facility	0.67713	$0.148\,S^2$	0.50
	Etc	0.27659	$0.332\,S^2$	0.72

1. S=Submerged area (*ha*) divided by average submerged area for each area type (*ha*)
2. Average submerged area (*ha*): Big city 875.3, Mid-sized city 303.0, Garden city 1,001.4, Rural area 761.2, Mountain area 139.6

Table 4-2. Household damage rates (%) per flooding depth (*m*) used for flood damage assessment

	Minimal Destruction	Partial Destruction	Complete Destruction	Loss
Flooding depth	0 ~ 0.5	0.5 ~ 1.5	1.5 ~ 2.5	> 2.5
Damage rates	5.5	40.0	83.0	100.0

Table 4-3. Rating scale for each criterion

Type	Classification	Measurement Scale Score
Land use disruption	Stream	1
	Crop / Pasture	5
	Grass Land	15
	Graveyard	50
	Rice Paddy	60
	Dry Field	70
	Residential Area	80
	Urban	100
Risk of flooding under different return period	Zone6 (No Flood)	1
	Zone5 (200yr)	20
	Zone4 (100yr)	40
	Zone3 (50yr)	60
	Zone2 (20yr)	80
	Zone1 (10yr)	100
Drainage capacity (Soil type)	Mvb (Drainage very good)	20
	Mva (Drainage very good or good)	40
	Rva (Drainage good)	50
	Anb (Drainage somewhat good or bad)	80
	Apc (Drainage somewhat bad or good)	100

Table 4-4. HEC-RAS simulations for five different alternatives

	10-yr Best	10-yr Worst	20-yr Best	20-yr Worst	50-yr Best	50-yr Worst	100-yr Best	100-yr Worst	200-yr Best	200-yr Worst
$3m$ x $3m$	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Alternative 1	0	6.803	0	7.252	0	7.917	0	8.612	0	8.847
Alternative 2	0	6.803	0	7.252	0	7.914	0	8.597	0	8.852
Alternative 3	0	6.534	0	6.997	0	7.590	0	8.074	0	8.467
Alternative 4	0	6.803	0	7.252	0	7.912	0	8.242	0	8.852
Alternative 5	0	6.534	0	6.996	0	7.541	0	7.847	0	8.399
$5m$ x $5m$	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Alternative 1	0	6.781	0	7.229	0	7.893	0	8.587	0	8.822
Alternative 2	0	6.781	0	7.229	0	7.891	0	8.572	0	8.827
Alternative 3	0	6.513	0	6.977	0	7.568	0	8.053	0	8.440
Alternative 4	0	6.781	0	7.229	0	7.889	0	8.217	0	8.826
Alternative 5	0	6.513	0	6.975	0	7.519	0	7.825	0	8.371

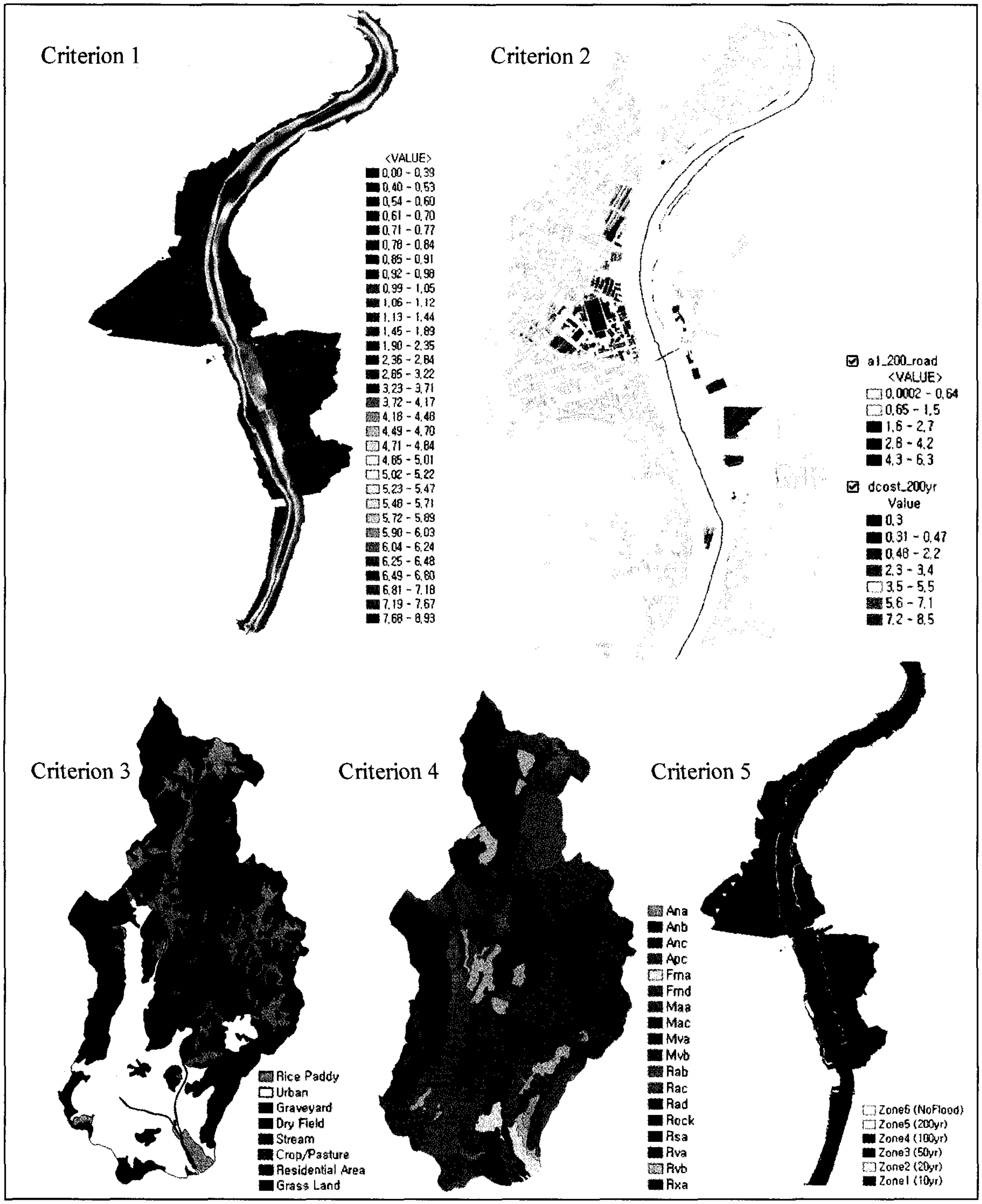


Figure 4-3. The five selected criterion maps

4.2.3 Defining the flood damage reduction alternatives

Flood control measures failed to contain the great Gradys flood of the summer of 1991, one of the worst in the Suyoung River Basin. Swelled by record summer rains, the Suyoung River area and many of its tributaries overflowed their banks, inundating an estimated 304 hectares in late August. The raging floodwaters also inflicted major damage upon levees and floodways. The key concept of the Suyoung River Basin flood control planning is how to decrease the huge flood inflow from the upstream portions of the Suyoung River Basin during the flood season. As shown below, various alternatives have been derived to find the best way to reduce flood damage. The following five candidate alternatives are considered in this study:

1) No Action (Before 1991 Gradys Flood): This alternative is to leave the floodplain area as it is with no additional action. Goicoechea et al (1982) remarks that the 10-year flood losses would be very small, but the 200-year flood would cause huge direct property damage. Potential flood damages, computed as a function of the flood water depth, damage cost to roads and the value of buildings have been calculated using a GIS environment.
2) Levees (After 1991 Gradys Flood): The most important and popular structural measures for controlling floods are levees, which use traditional engineering tools and are still the most commonly used structures protecting communities from inundation in many countries. They alter only high flows of water by restraining entry of flood waters to the low-lying areas (Canada 2000). After the 1991 Gladys flood event, one of the major communities (Banyeo-Dong) which had severe flood damage totaling around $1,500,000, built levees along the east side of the

river.

3) Channelization: Floods in the Suyoung River have demonstrated that levees alone do not provide sufficient protection against flooding on a large river, and other methods of flood control need to be implemented along the Suyoung River. Channelization of a stream may be undertaken as a flood control measure, with the goal of giving a stream a sufficiently large and deep channel so that flooding beyond those limits will be minimal.

4) Pumping: In a closed area of a river basin or an area where the ground level is particularly low, one possible solution may be to install pumping facilities to drain the flood water, regardless of the location of the waterway or river. Levee construction frequently necessitates the installation of pumping facilities to minimize flooding behind the levee (Canada 2000). Pump stations are used for pumping water stored behind a levee (interior sump) into the main river. For this research, four pump stations with a capacity of 3,800 m^3/min are installed along the upstream side of the Suyoung River.

5) Combination of channelization and pumping: This alternative combines channelization with pumping for more effective flood control.

4.2.4 Hydraulic and hydrologic data development

The purpose of this section is to apply, in a combined fashion, the latest hydrologic and hydraulic modeling tools and recently developed GIS software to the flooding problem in the Suyoung River Basin. The programs, the Hydrologic Engineering Centers Hydrologic Modeling System (HEC-HMS) and the Hydrologic Engineering Centers

River Analysis System (HEC-RAS), allowed for the easy creation and transfer of modeling data sets relating to the Suyoung River. HEC-GeoRAS is a set of procedures, tools, and utilities for processing geospatial data in ArcGIS using a GUI. The interface allows the preparation of geometric data for import into HEC-RAS and processes simulation results exported from HEC-RAS.

4.2.4.1 Developing the HEC-HMS model

The HEC-HMS is designed to simulate the precipitation-runoff processes of dendritic watershed systems and allows the viewing of results in tabular or graphical form from the basin map. There are three sub-sections; the basin model, the meteorological model, and the control model. Each component represents a different element of the model. The physical representation of a watershed is accomplished with a basin model, such as basin areas, river reach connectivity or reservoir data. Likewise, meteorological data analysis is performed by the meteorological model and includes precipitation, evapotranspiration, and snowmelt. Finally, the time span of a simulation is controlled by control specifications such as when a storm occurred and what type of time interval we want to use in the model. A simulation run is created by combining a basin model, meteorological model, and control specifications. Run options include a precipitation or flow ratio, capability to save all basin state information at a point in time, and ability to begin a simulation run from previously saved state information (http://www.waterengr.com/HECHMS.html).

Figure 4.4 shows the HEC-HMS generated schematic of the model used for hydrologic analysis of the Suyoung River. Analysis on various size floods is important to develop comprehensive floodplain mapping in a river basin. For example, analyses on various floods from as small as a 10-yr flood to as large as a 200-yr flood allow engineers check the damages to different regions and facilities. Therefore, in this study five flood recurrence intervals are selected to cover various possible flood damages. In a statistical sense, floods with any design frequency can occur at any time of the year. Calculated HEC-HMS results for the five different flood recurrence intervals are shown in Table 4.5. The table also shows some of important calculated flow characteristics including design floods, time to peak by location and basin information.

4.2.4.2 Developing the HEC-GeoRAS model

The HEC-GeoRAS model is an ArcGIS extension that provides the user with a set of procedures, tools, and utilities for the preparation of GIS data for import into HEC-RAS and generation of GIS data from RAS output. HEC-GeoRAS extracts terrain information stored in TINs or DEM and generates a HEC-RAS import file containing geometric attribute data from an existing DTM and selected complementary data sets, such as river reaches, bank lines, bridges, inefficient flow areas, blocked obstructions, and others. Post-hydraulic analysis results generated by HEC-RAS can then be exported back to HEC-GeoRAS and converted to a GIS format for spatial analysis and automated floodplain delineation (Bedient and Huber 2002). HEC-GeoRAS was used to create an HEC-RAS import file, process water surface profile data exported from HEC-RAS, and perform floodplain mapping for several floodplain alternatives concerned with flood control. In this research, five floodplain mappings we are developed including the 10-yr, 20-yr, 50-yr, 100-yr, and 200-yr floodplains. Figure 4.5 shows that HEC-GeoRAS performs spatial analyses and mappings by importing geometric data from DTMs.

4.2.4.3 Developing the HEC-RAS model

The HEC-RAS model was used for all hydraulic analyses of the Suyoung River. HEC-RAS is an integrated package of hydraulic analysis program, and has several improvements over that of the original HEC-2 analysis model. HEC-RAS is capable of modeling subcritical, supercritical, and mixed flow regime water surface profiles (Center 1997). Other special features include optimization of flow splits, automatic roughness calibration, and sophisticated multiple-opening bridge and culvert analysis. In addition, the program has a number of special capabilities related to the analysis of culverts and bridges at roadway crossings.

A HEC-RAS hydraulic model of a $3.58km$ reach of the Suyoung River was successfully created using entirely digital topographic data in a GIS format and the HEC-GeoRAS program (Bedient and Huber 2002). The Korean Ministry of Construction and Transportation (MOCT) provided all cross-sectional elevation data in a HEC-2 format. Once the geometry and flow files are complete, the model is run to calculate water surface elevations at each cross-section. The output of HEC-RAS is either provided in the form of tables or as a plot like the one shown in Figure 4.6.

4.3 GIS procedure of application

The purpose of this section is to describe the methodology employed to integrate the DEM with existing surveyed channel elevation data (HEC-RAS) to obtain accurate floodplain delineation maps. The developed maps were used as a base map for evaluating candidate alternatives. This methodology is important as it can increase the accuracy of stream channel data and reduce inherent imprecision in the terrain data. This imprecision of stream channel and terrain morphology in a DEM strongly affects the result of an MCDA. Tate et al (2002) showed that the resulting integrated terrain model accurately describes both the general floodplain and stream channel morphology. Once the flood inundation area is delineated, useful floodplain management information is provided.

In this section, the differences between an adjusted DEM and an unadjusted DEM, as compared the result with the original 1991 Gradys flood map, are evaluated using standard metrics. The impact of using each DEM for floodplain analysis in the next chapter were examined.

In this case study, DEM sets have 3*m* by 3*m* and 5*m* by 5*m* grid resolution. The overall methodology for terrain modeling used as a first step for this research is represented in Figure 4.7. In step 1, computed flood frequency estimates are based on more than 25-years of annual peak-flow records, compiled from 1978 through 2005, from the Pusan weather station peak-flow data. Flood frequency estimates for the Suyoung River typically are presented as a set of peak flows and the associated recurrence intervals. After the interval of occurrence data was obtained, it was utilized as input data for the Suyoung River Basin hydrologic model. As a result of step 1, the HEC-HMS hydrologic model was developed. In step 2, the resulting peak flows from hydrographs generated by the hydrologic model were used as input to a HEC-RAS model created for a specific portion of the Suyoung River Basin. The hydraulic model was created in conjunction with the HEC-GeoRAS extension, using 3- or 5-*m* resolution DEM. HEC-GeoRAS was used to convert the resulting water surface elevations into specific digital floodplains. In the final step (step 3), these digital floodplains were combined with additional GIS data to evaluate flood damage reduction alternatives (Bedient and Huber 2002).

Table 4-5. Calculated flow characteristics including design floods, time to peak by location and basin information

Data Series	Duration	Return Period	Heoidong Dam		Sukdaechun Joint		Onchunchun Joint		Suyoung River Downstream	
			Q_P (*cms*)	T_P (*cms*)	Q_P (*cms*)	T_P (*cms*)	Q_P (*cms*)	T_P (*cms*)	Q_P (*cms*)	T_P (*cms*)
Annual maximum	12-hour	10-yr	512.6	7.42	682.2	7.25	1034.5	7.00	1071.9	7.00
		20-yr	642.5	7.25	849.7	7.17	1280.9	6.83	1325.3	6.92
		50-yr	817.5	7.08	1076.3	7.00	1614.4	6.75	1668.8	6.75
		100-yr	956.2	7.00	1254.7	6.92	1876.3	6.67	1940.4	6.75
		200-yr	1100.0	6.92	1439.2	6.92	2115.9	6.67	2190.1	6.58
Basin characteristics			HD		J3		J4		J5	
Watershed area $A(km^2)$			99.84		128.05		192.14		199.60	
Channel length $L(km)$			20.54		23.70		27.83		29.54	
Channel slope $S(H/L)$			0.0341		0.0301		0.0257		0.0243	
Effective basin width $A/L(km)$			4.8606		5.4015		6.9039		6.7554	
Form factor A/L^2			0.2366		0.2278		0.2481		0.2286	
CN (AMC-III)			75.87		77.04		79.82		80.27	

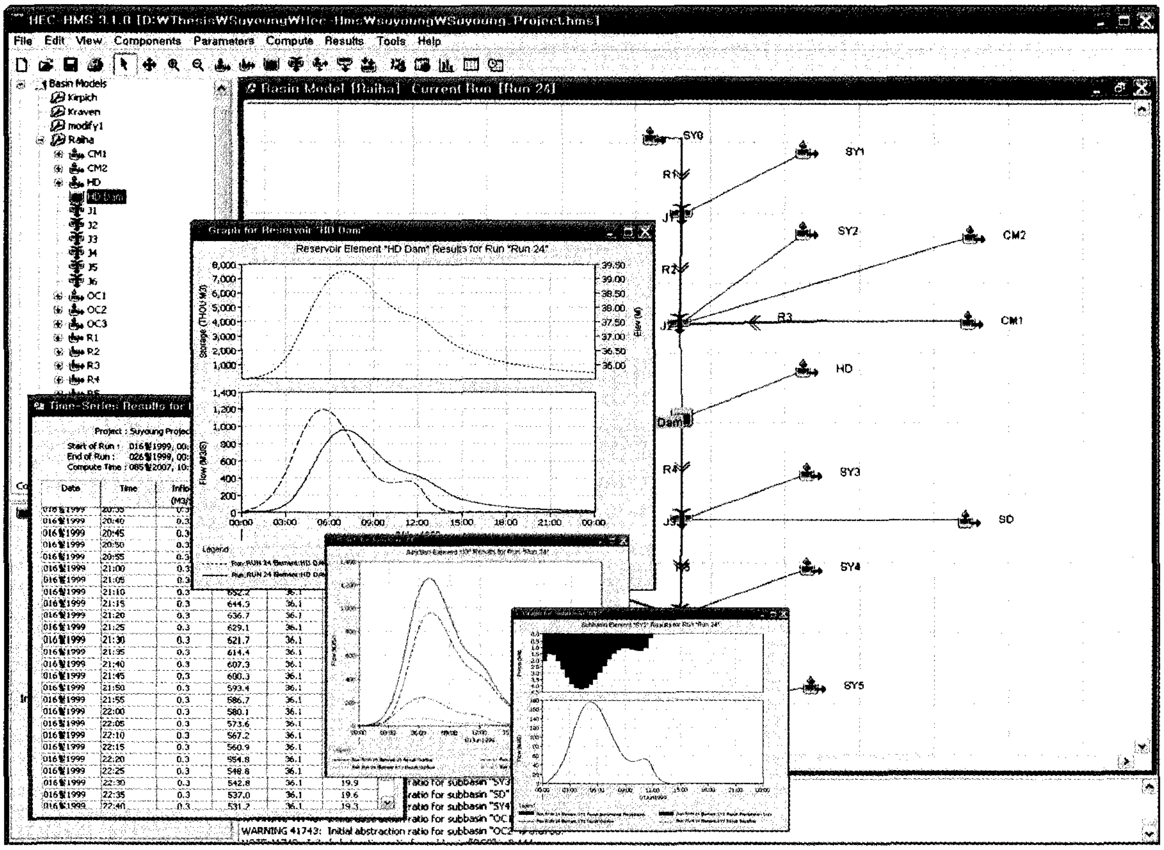


Figure 4-4. HEC-HMS schematic for the Suyoung River Basin

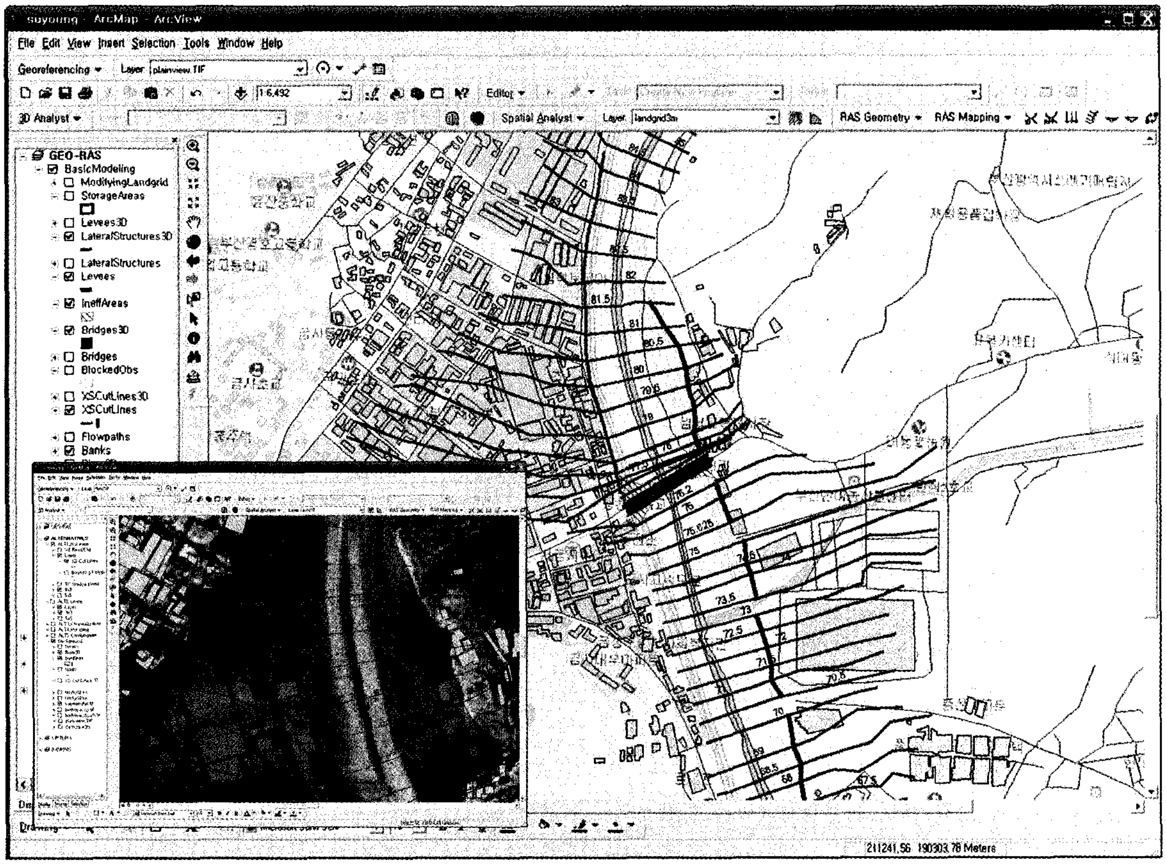


Figure 4-5. Floodplain delineation overlaying various layers using HEC-GeoRAS

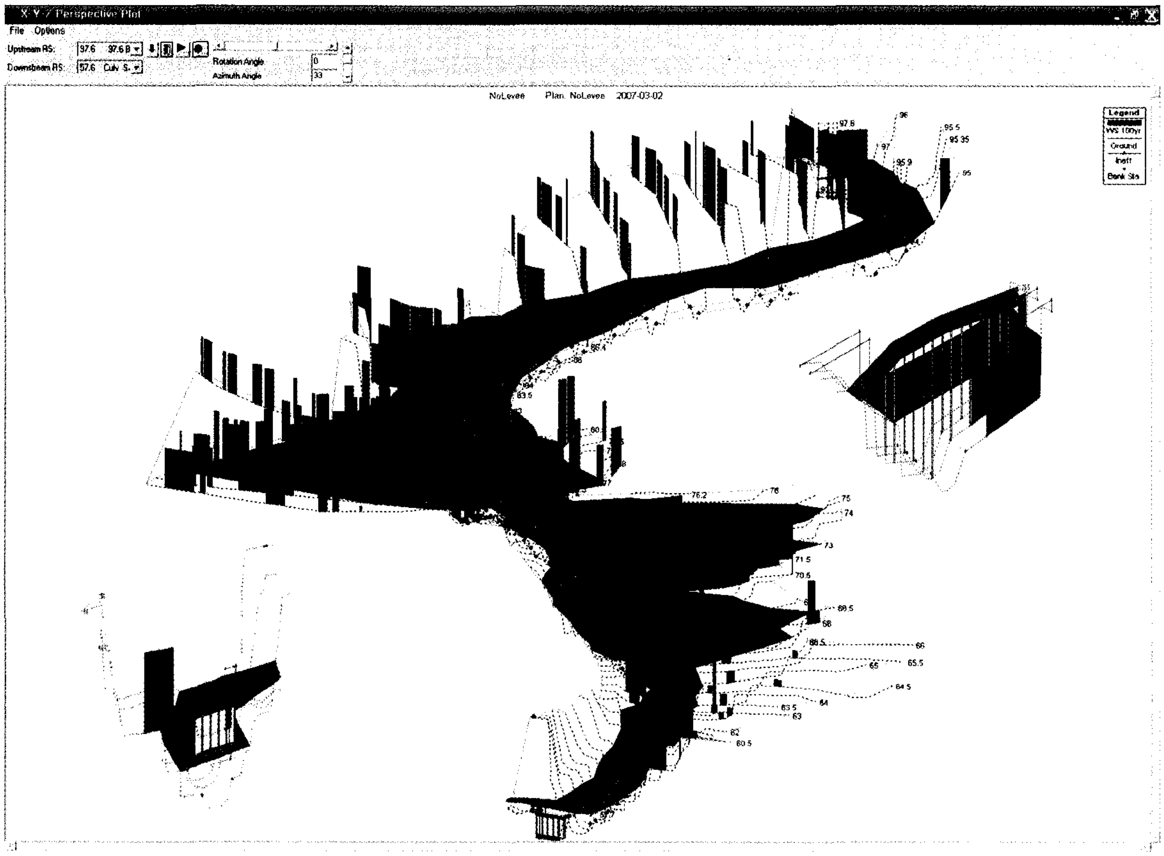


Figure 4-6. HEC-RAS three-dimensional plot of the Suyoung River Basin

4.3.1 Terrain modeling

A DEM is the most essential and important piece of data for flood inundation simulation using a hydraulic model. However, it is necessary to manipulate the DEM according to the format required by the model, and to integrate the DEM with existing surveyed channel elevation data (HEC-RAS) to represent as accurately as possible the important stream channel morphology and ground features (Jones et al. 2001).

4.3.1.1 Data quality for terrain representation

It is important to note that terrain elevation data accurate to 1-foot would greatly improve the accuracy of floodplain mapping and is necessary to credibly map differences in 10- and 200-year floods that differ in elevation by less than 1-foot (Bedient and Huber 2002; Maidment 2002; Shim 1999; Tate et al. 2002; Zerger 2002).

For the reasons described above, Bedient and Huber (2002) stress the widely available 50- or 100-*m* resolution DEMs provided insufficient topographic detail for accurate hydraulic analysis of river channels, especially in extremely flat areas. Thus, in order to ensure the success of floodplain analysis as a first step of MCDA, it is necessary to use high accuracy maps to get sufficiently accurate detail for flood inundation mapping. The problem, unfortunately, is that high accuracy maps with a resolution in stream channels sufficient for hydraulic modeling are not widely available (Tate et al. 2002). Hence, the next logical step is improving data quality for terrain representation. Creating an accurate stream channel DEM from existing surveyed channel elevation data could possibly alleviate the aforementioned shortcomings. This would provide a good representation of the general landscape and contain additional detail within the stream channel (Lim 2001; Shrier 2004; Tate et al. 2002; Zerger 2002). In this research, an

Arcview Avenue program developed by Eric Tate (1998) was used to integrate HEC-RAS and the DEM. Details of the combining technique used in this process are described in the work of Eric Tate (1998).

4.3.1.2 Formation of an integrated terrain model

In order to produce a floodplain map, accurate topographic information is required as stated early in this section. While this is desirable, this is not always readily available. The only DEM available for the Suyoung River Basin has a low-resolution. The potential impact of such imprecision is illustrated in Figure 4.8, which shows significant differences between a relatively low-resolution DEM and comparatively high-resolution terrain TIN after integrating the HEC-RAS cross-section data into the DEM.

Figure 4.9 shows the stream channel elevation difference between the original and adjusted DEM. HEC-RAS data very accurately describes stream channel shape since it is based upon the surveyed channel elevation collection. However, the terrain description within the channel using an unadjusted DEM is inaccurate because the data describes channel information too coarsely. After integrating HEC-RAS stream channel data into each DEM location, the adjusted DEM shows a quite different stream channel shape relative to the original DEM. Outside of the stream channel, ArcGIS is still retaining the original DEM data format. However, inside the channel, information such as numerous cross-section lines, the stream centerline, and the left and right banks were replaced with integrated cross-section data (Jones et al. 2001; Jones et al. 1998; Lim 2001; Tate et al. 2002; Zerger 2002). The coarseness of existing DEM data explains why the low-resolution DEM surface used in MCDA techniques currently is not suitable for the terrain representation required for floodplain analysis.

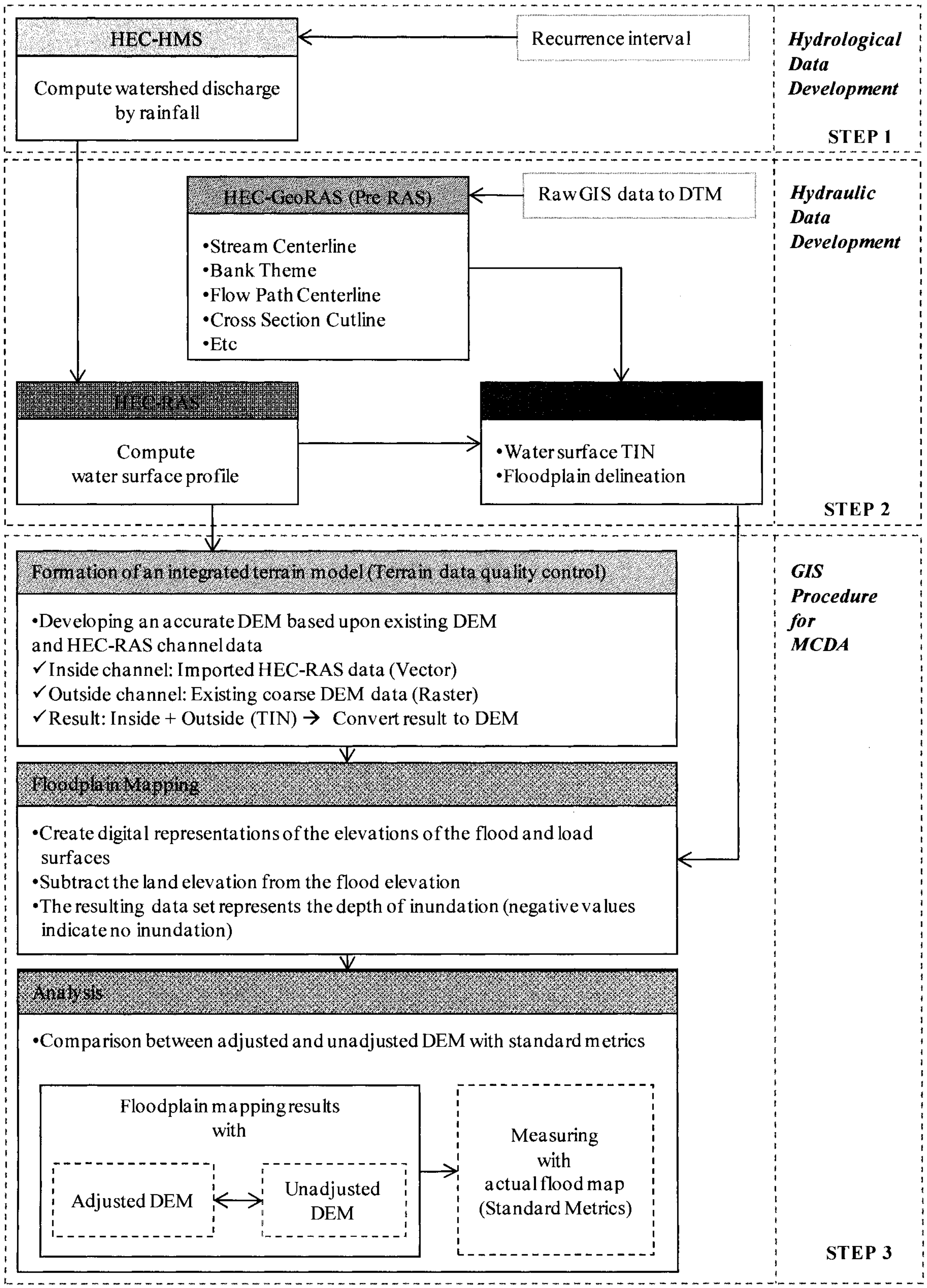


Figure 4-7. Schematic diagram of the overall methodology for terrain modeling

Various layers such as houses, tenement houses, temporary buildings, apartments, and rice paddy fields were added to describe the Suyoung area in three-dimensional layers (Figure 4.10). Once the terrain model was complete, the next step was to delineate the floodplain.

4.3.2 Floodplain mapping

HEC-RAS calculated the water surface elevation and the computer program HEC-GeoRAS (using the adjusted DEM as a base map) was used to create an HEC-RAS import file, process water surface profile data exported from HEC-RAS, and perform floodplain mapping for several floodplain alternatives concerned with flood control. During the data import step, these elevations were brought into ArcGIS.

The main concept of flood inundation is fairly simple and straightforward. The DEM representing land terrain elevation is subtracted from the water surface elevation coverage that was produced from HEC-GeoRAS, yielding positive values (inundated areas) where flooding will occur whenever water surface elevation is greater than that of the land terrain. The resulting grid data set with a cell size of 3- or 5-*m* was then converted to an ASCII format for storage, display, and further analyses using Matlab (Jones et al. 2001). The converted data result was then used in the next step, MCDA of the Suyoung River Basin.

Figure 4.10 shows the level of detail that can be obtained by building a detailed TIN surface model of the Suyoung River basin that includes buildings, and roads. The results of floodplain delineation are floodplain maps, in which the extent of flooding can easily be compared to the locations of structures of interest such as businesses, schools, and homes. In five figures (Figure 4.11 ~ 4.15), the floodplain delineation rendering for the 10-yr, 20-yr, 50-yr, 100-yr and 200-yr floods on the Suyoung River is shown. With this graphical view, one can easily analyze flood damages such as how many buildings are submerged, or how many roads are inundated, under different return periods by simply comparing with other frequencies of design floods.

As is commonly known, flood inundation refers to damage sustained by items which have been in direct contact with flood waters. Table 4.6 shows floodplain area and perimeter from cross-section 57.5 to 97.6, after each occurrence interval. Table 4.7 shows the submerged building profile under different return periods. This estimation could not be verified since there was no relevant field data from the study area. However, it is felt that the simplicity of this method will allow it to be used for flood recovery or prevention works as a quick estimate of flood damage.

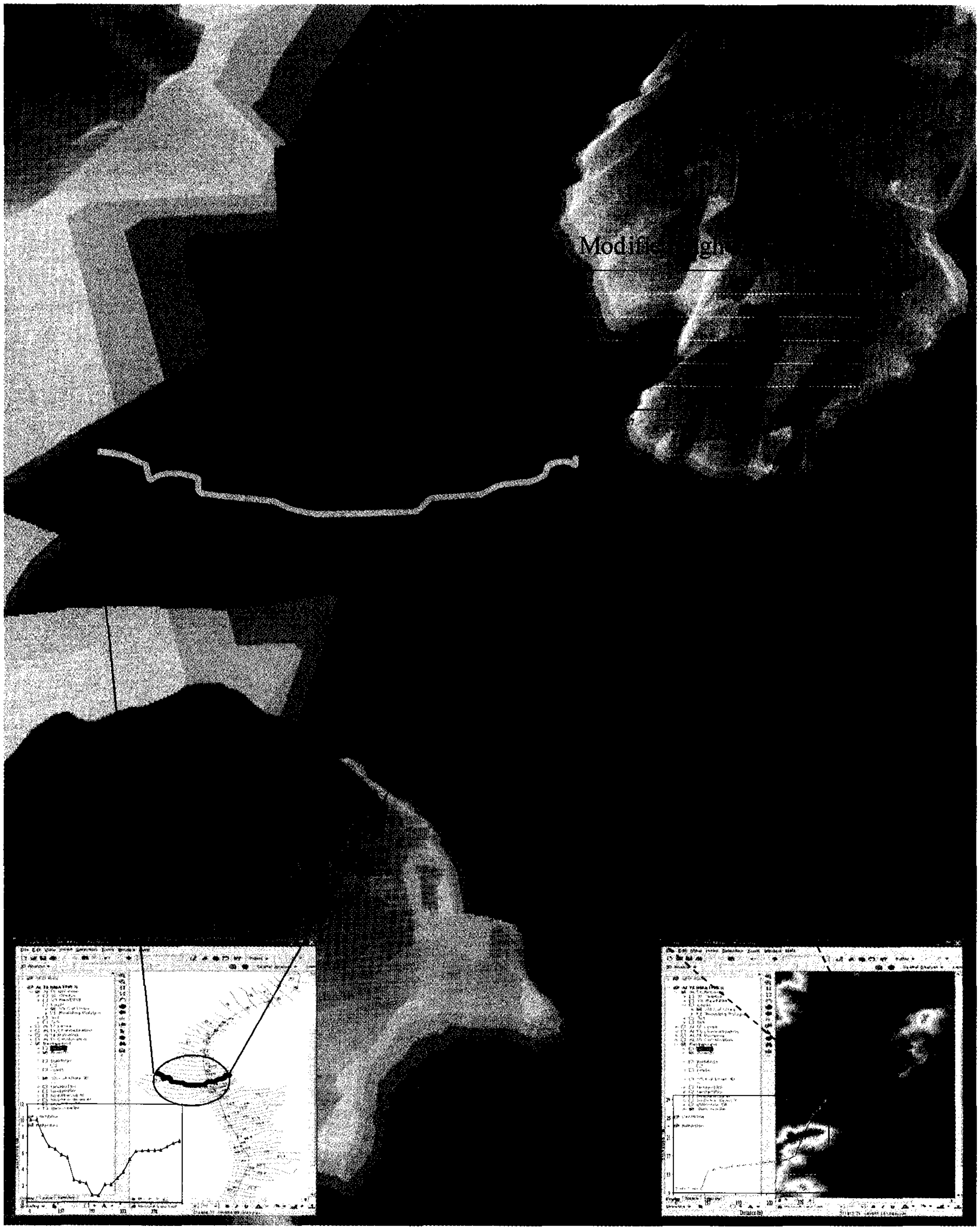


Figure 4-8. Three-dimensional TIN terrain modeling approach of the Suyoung River Basin

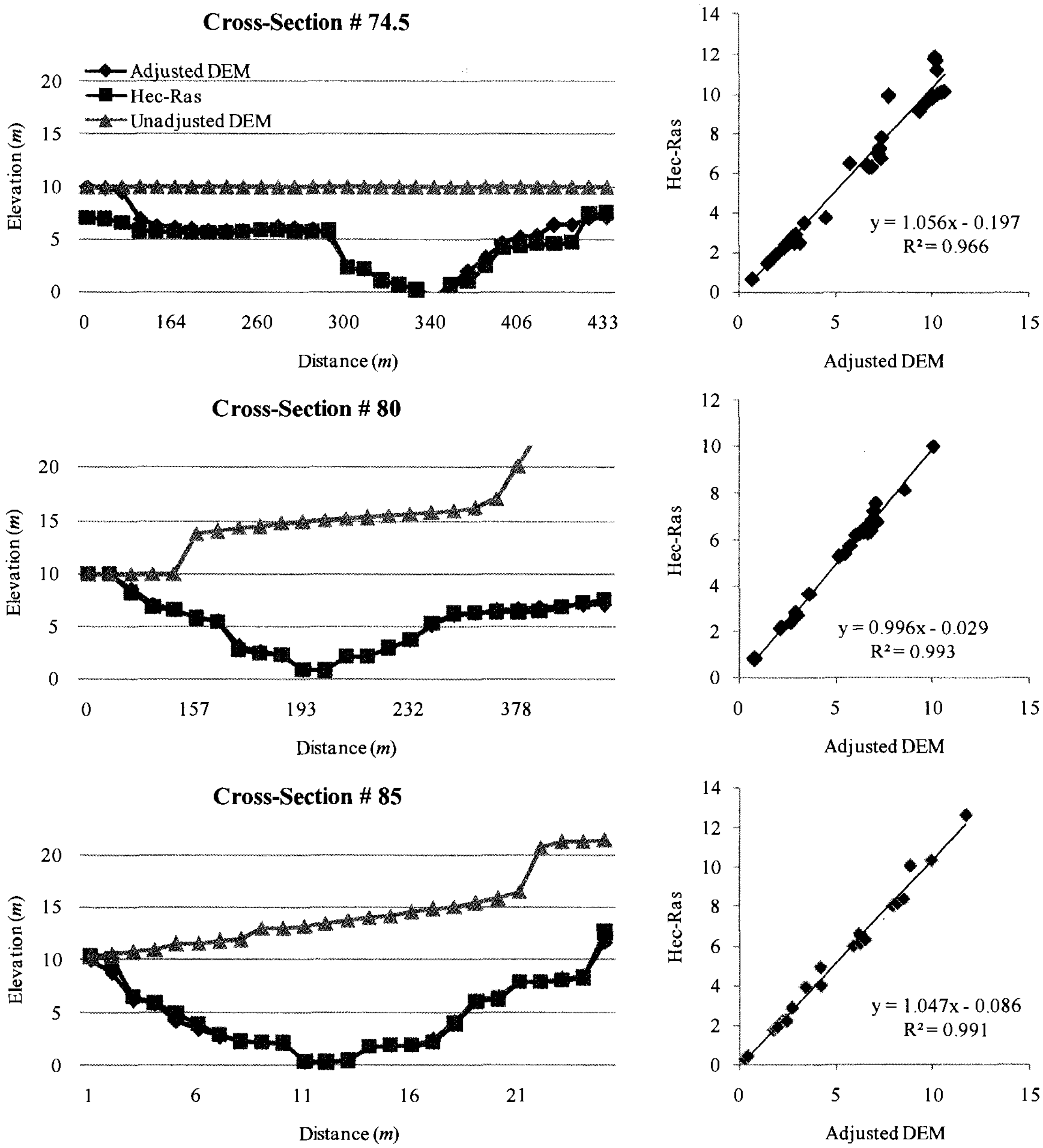


Figure 4-9. Cross-section profile comparison: adjusted DEM, HEC-RAS cross-section, and unadjusted DEM

Table 4-6. Flood inundation area and perimeter at each flooding (Alternative 1, CS 57.5~97.6)

Flood	Area (*ha*)	Perimeter (*km*)
10-yr	35.62	103.50
20-yr	37.86	105.48
50-yr	44.50	114.96
100-yr	81.19	126.96
200-yr	87.38	126.90

Table 4-7. Submerged building profile at each flooding

Flood	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
10-yr	5	5	5	5	5
20-yr	10	10	11	10	9
50-yr	40	39	83	14	32
100-yr	183	149	128	115	101
200-yr	205	188	184	179	169

Figure 4-10. Final potential level of three-dimensional view of the Suyoung River Basin

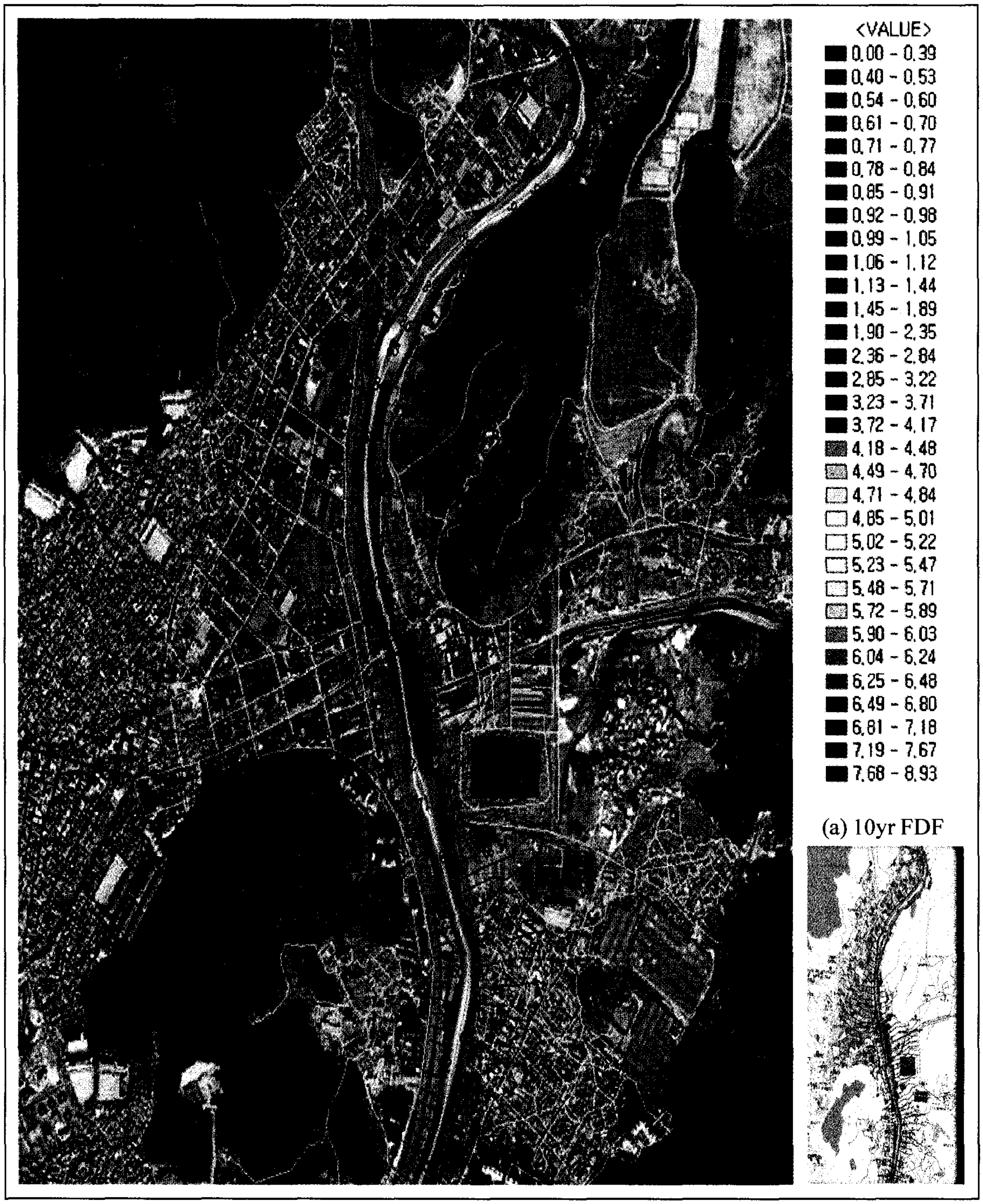


Figure 4-11. 3-D view of flood-affected areas based upon a 10-year event

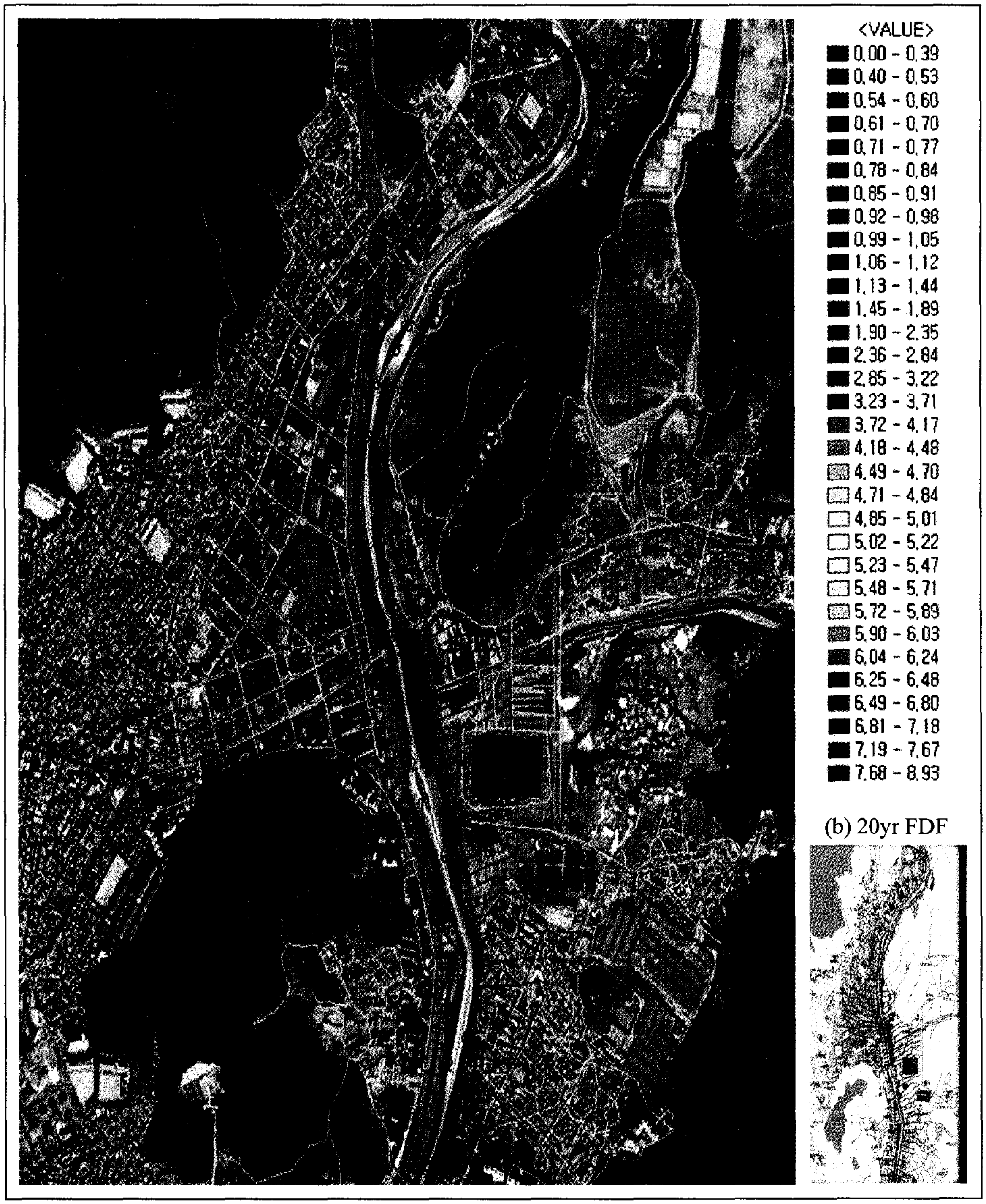


Figure 4-12. 3-D view of flood-affected areas based upon a 20-year event

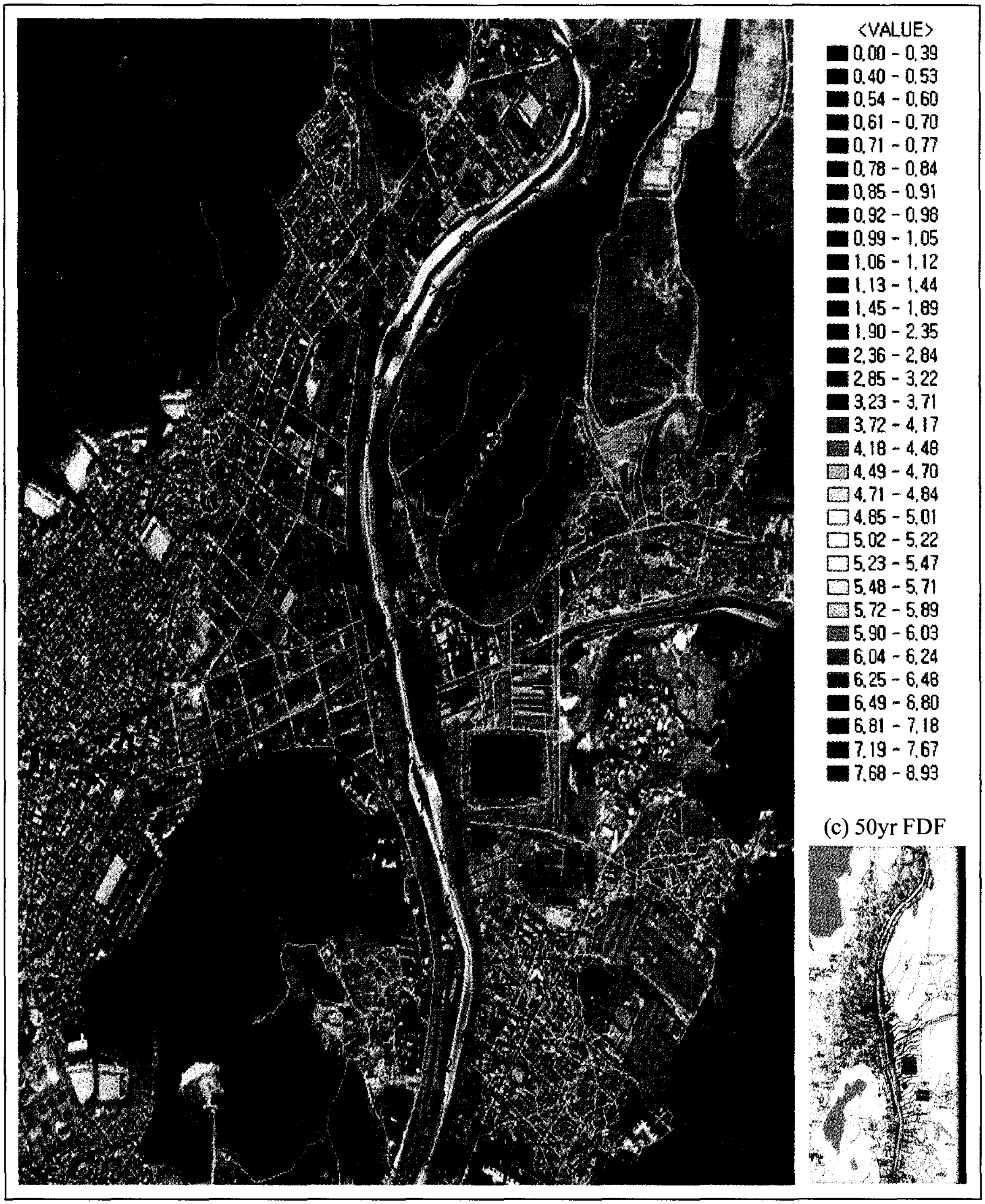


Figure 4-13. 3-D view of flood-affected areas based upon a 50-year event

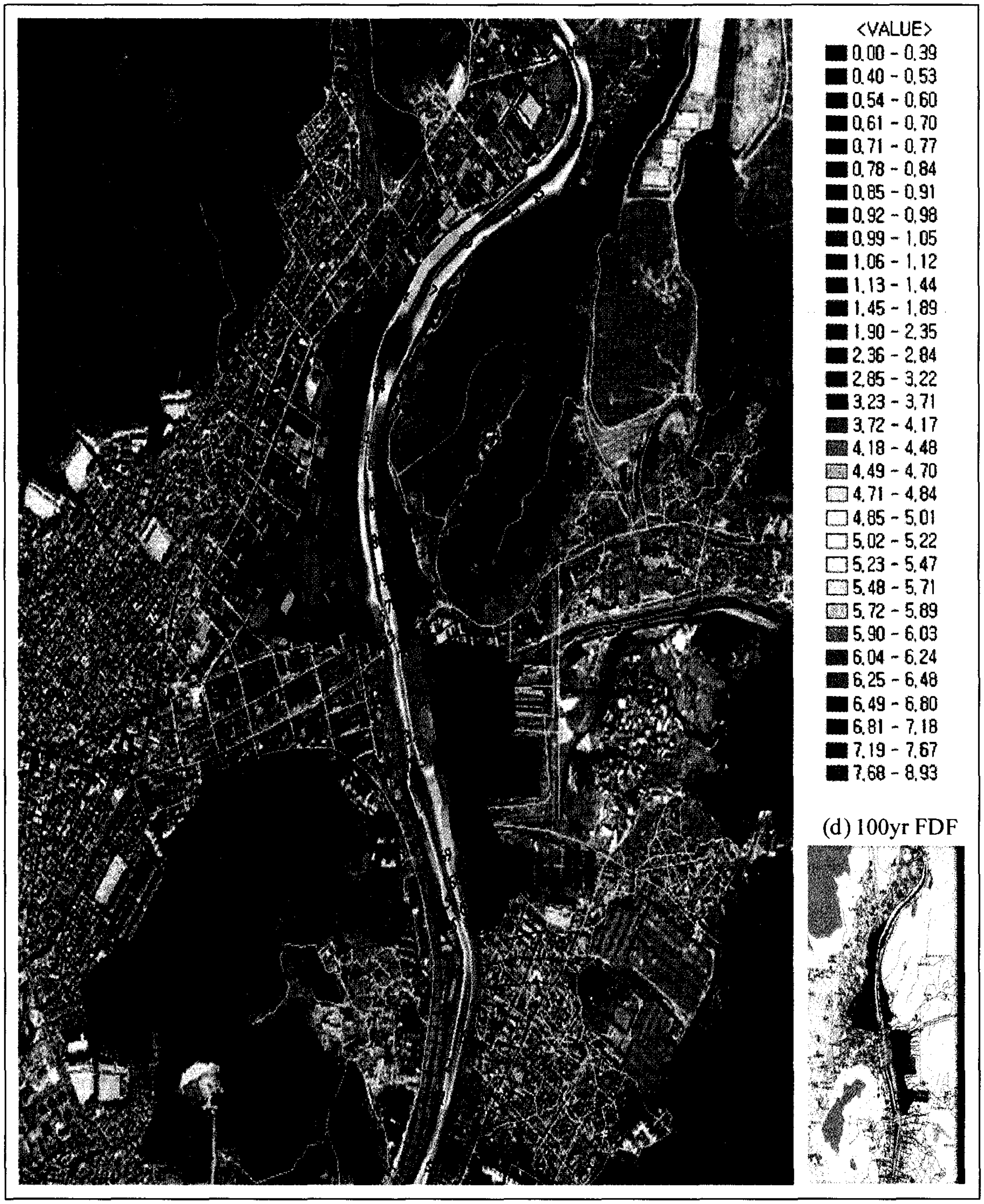


Figure 4-14. 3-D view of flood-affected areas based upon a 100-year event

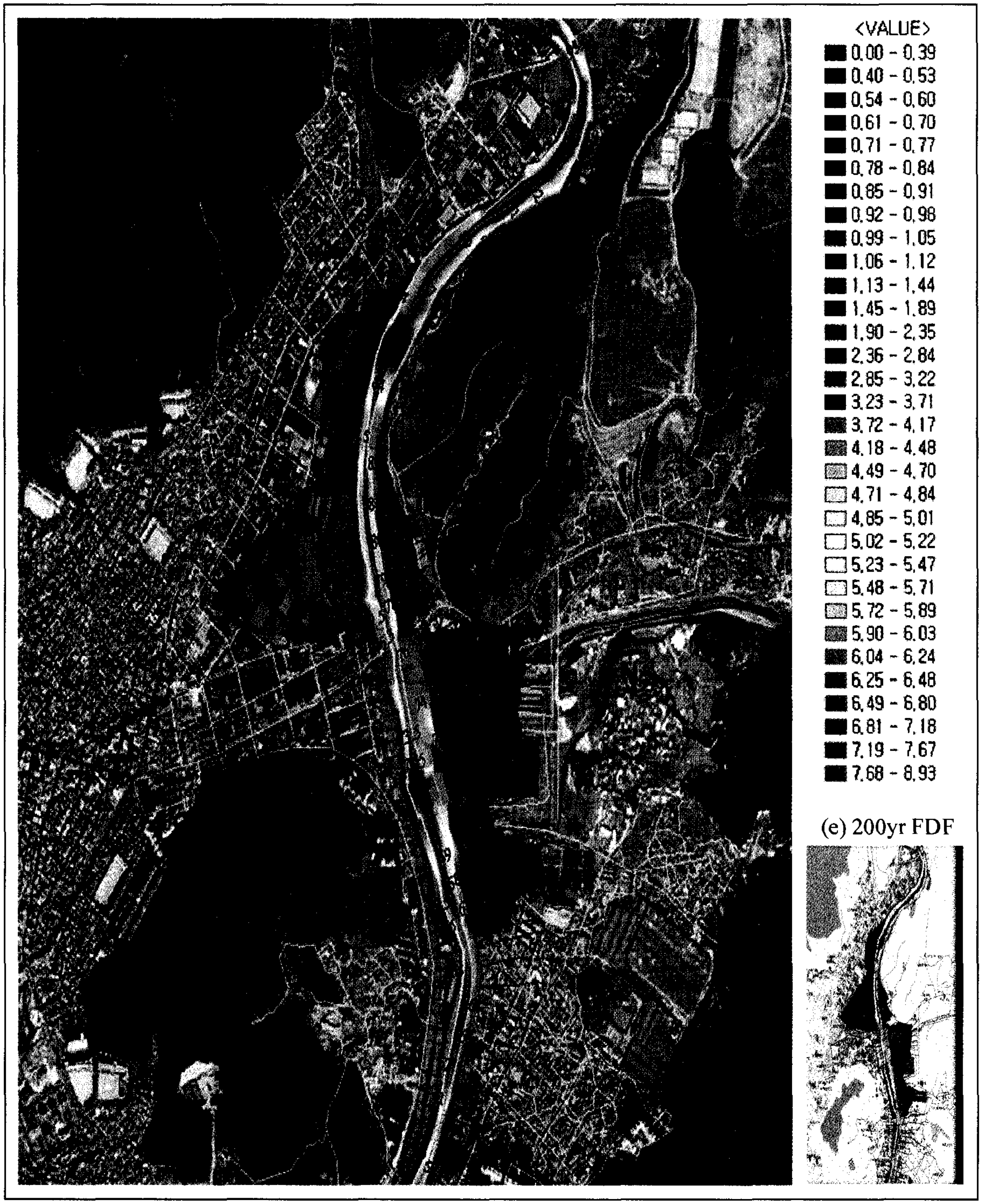


Figure 4-15. 3-D view of flood-affected areas based upon a 200-year event

4.3.3 Comparison of an adjusted DEM and an unadjusted DEM

The left-hand figure in Figure 4.16 shows the unadjusted DEM. It provides insufficient topographic detail of the stream channel of the Suyoung River, especially in extremely flat areas. The right-hand figure represents the DEM adjusted by integrating the raw DEM data with existing surveyed channel elevation data (HEC-RAS). The adjusted DEM using actual stream channel elevation data depicts stream channel morphology details accurately enough for floodplain mapping simulation. It is obvious from Figure 4.16 that the existing DEM is not sufficiently precise to be useful unless it is adjusted.

To further illustrate the problems associated with using the unadjusted DEM, Figure 4.17 shows the results of performing floodplain mapping using the adjusted DEM and the unadjusted DEM. For the purposes of this comparison, a 100-yr design flood was assumed as representative, and was used to show the elevation differences between the resulting models. The extent of the flood area from the adjusted DEM is also shown on the unadjusted DEM. As the figure indicates, floodplain mapping without modifying the DEM gives completely erroneous results. This is due to the inaccuracy of elevation information in the raw DEM. Since the detail of stream channel elevation is a key factor in floodplain analysis, using an adjusted DEM for floodplain mapping should result in significant improvement of floodplain mapping accuracy.

4.3.4 Comparison of simulation with observed flood extent map using standard metrics

The Hazards U.S. Multi-Hazard (HAZUS-MH) developed by the Federal Emergency Management Agency (FEMA), is a nationally applicable standardized methodology and software program that estimates potential losses from earthquakes, floods, and hurricane winds. The Flood Information Tool (FIT) is an ArcGIS extension designed to process user-supplied flood hazard data into the format required by the HAZUS-MH Flood Model. The FIT, when given user-supplied inputs (e.g., ground elevations, flood elevations, and floodplain boundary information), computes the extent, depth and elevation of flooding for riverine and coastal hazards (Scawthorn et al. 2006). However, use of the FIT requires the users to provide input spatial data. This includes terrain elevation information, flood elevation and floodplain boundary (Committee on Floodplain Mapping Technologies 2007).

In general, the value of flood elevation and floodplain boundary is highly dependent on the quality of terrain elevation data. Ground elevation information has a multitude of other uses in addition to floodplain mapping. FEMA publishes guidelines and recommendations for flood hazard mapping partners, among which is "Appendix A: Guidance for Aerial Mapping and Surveying" (FEMA 2003). This document is very important because it describes the technical standards for base mapping for Digital Flood Insurance Rate Map (DFIRM) development. With respect to elevation data, Appendix A states (FEMA, 2003, p. A-5): FEMA has reduced the complex requirements to two standard choices for digital elevation data, expressed as equivalent contour intervals (Committee on Floodplain Mapping Technologies 2007):

1) Two-foot equivalent contour interval for flat terrain (Accuracy_Z = 1.2 feet at the 95 percent confidence level). This means that 95 percent of the elevations in the dataset will have an error with respect to true ground elevation that is equal to or smaller than 1.2 feet (0.37 meter).

2) Four-foot equivalent contour interval for rolling to hilly terrain ($Accuracy_Z$ = 2.4 feet at the 95 percent confidence level). This means that 95 percent of the elevations in the dataset will have an error with respect to true ground elevation that is equal to or smaller than 2.4 feet (0.73 meter).

The HAZUS-MH methodology specifies the accuracy of the DEMs required for effectively determining the floodplain. It does not provide a process to adjust lower accuracy DEMs to higher accuracy DEMs as developed in this research. The enhanced DEMs developed in this research, however, match the requirements stated in HAZUS-MH.

A comparison between the actual 1991 Gradys flood map and the simulated 100-yr flood inundation map utilizing an adjusted DEM (section 4.3.2 and 4.3.3) has been conducted. The comparison was made only with respect to flooded areas.

The computed peak discharge and flood extent are very close to both the actual peak discharge and the actual flood extent. Figure 4.18 shows the flood extent in relation to a satellite image of the Suyoung River study area. The cross-section line and flood extent for a 100-yr design flood are also depicted. During the Gradys flood, the towns of Geumsa and Banyeo were adversely impacted. The flood inundation map for the Suyoung basin (Figure 4.18) shows the approximate areas of Geumsa and Banyeo along the Suyoung River during inundation with flood water. The blue lines on the digital raster graphics map depict the Suyoung River's stream centerline. This map also shows the HEC-GeoRAS simulation in conjunction with the estimated flood extent for the Suyoung area, constructed by the city of Pusan based upon observed reports from the 1991 Gradys flood event.

Table 4-8. Comparison of actual flood and simulation (Standard metrics)

Area	Peak Discharge (m^3/s)		Inundated Area (km^2)	
	1991 Gladys	Simulation	1991 Gladys	Simulation
Geumsa	924.3	957.0	0.65	0.60
Banyeo	1190.7	1255.6	0.88	0.75

Table 4.8 shows that this compared well to the modeled peak flow at the same location, with only a 4.6% flow difference. The computed inundation extent agrees closely with the case of the 1991 Gladys flood. An 88.2% average accuracy between the Gladys flood and the simulation shows that the differences are relatively small.

Overall, the simulated results compare very well with what actually occurred during the flood. However, on the lower reaches of the Suyoung River there was some discrepancy. On the east side of the river model (Geumsa area), some water of an undetermined amount was predicted to overflow the channel banks and flow southward beyond the flood extent of the actual 1991 Gradys flood. The most likely reason for this discrepancy is that 5*m* DEM data is not fine enough to accurately resolve the spatial detail in the area of interest, and therefore the extent of the flood over flat terrain such as that found around the downstream area of the Suyoung River. This comparison indicates that higher resolution DEM data is needed to provide a more comprehensive flood inundation map. The results were generally similar to the observations during the 1991 flood event. In addition, the adjusted DEM satisfied the technical standards of FEMA for base mapping for DFIRM development as shown in Figure 4.9. It is believed that the flood inundation simulation based upon the adjusted DEM is realistic.

After the 1991 Gladys flood, a levee was built on Banyeo-Dong, and Figure 4.19 shows that there has been no more flood inundation. Finally, this floodplain map is useful for regulation, planning and management of storm water related issues.

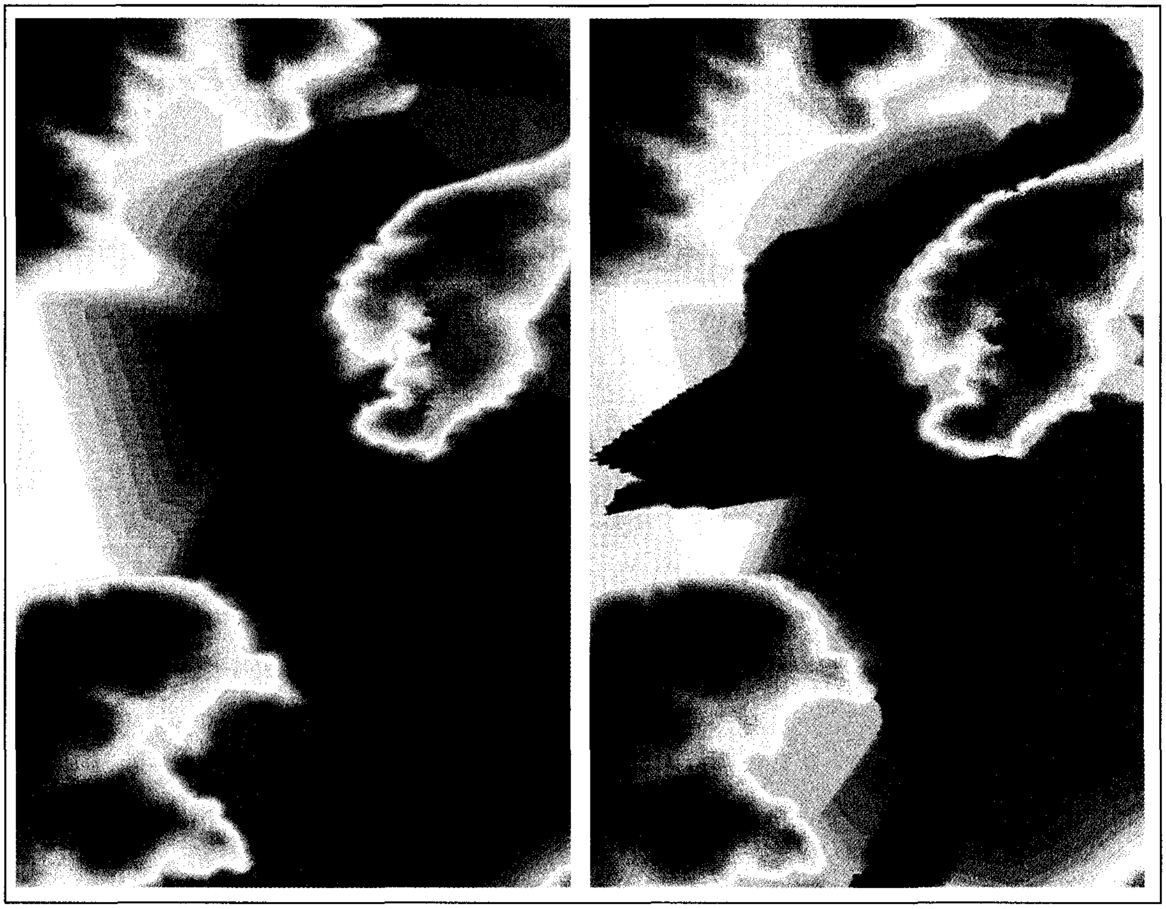


Figure 4-16. Comparison of unadjusted (left) and adjusted land terrain elevation (right)

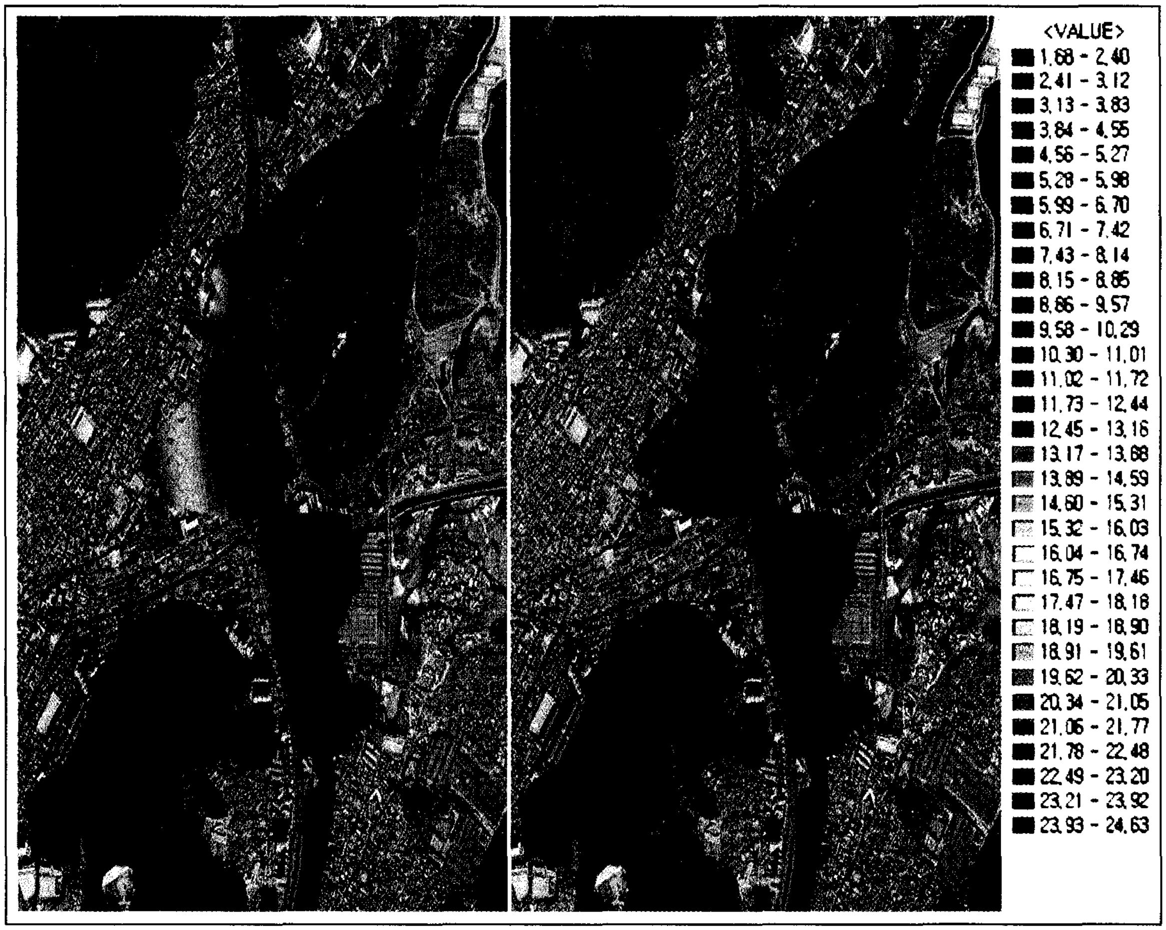


Figure 4-17. Suyoung floodplain mapping: Unreasonable 100-yr flood results with the unadjusted DEM (left) vs. the adjusted DEM (right)

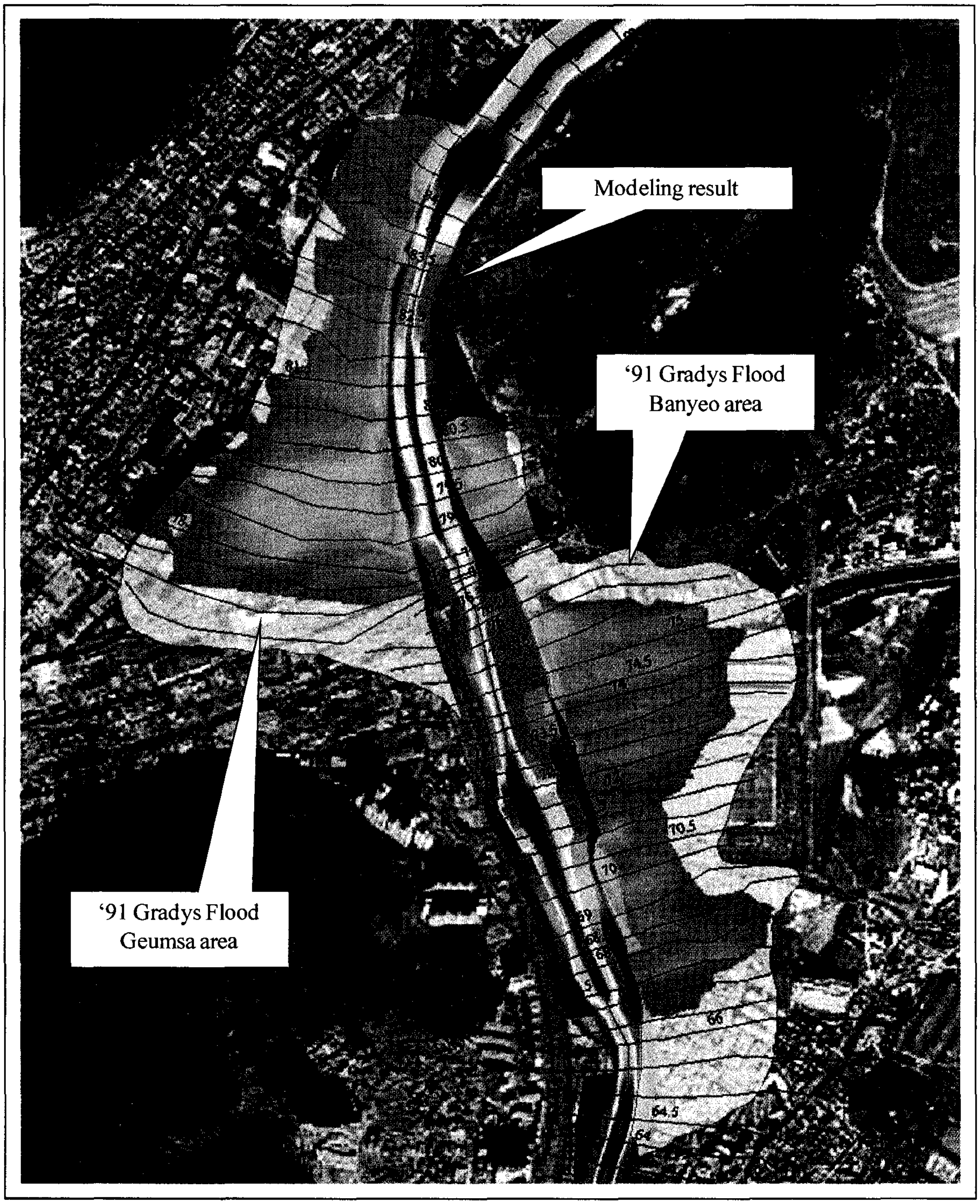


Figure 4-18. Comparison of observed 1991 Gradys flood extent provided by the city of Pusan and the simulation result (100-yr Flood)

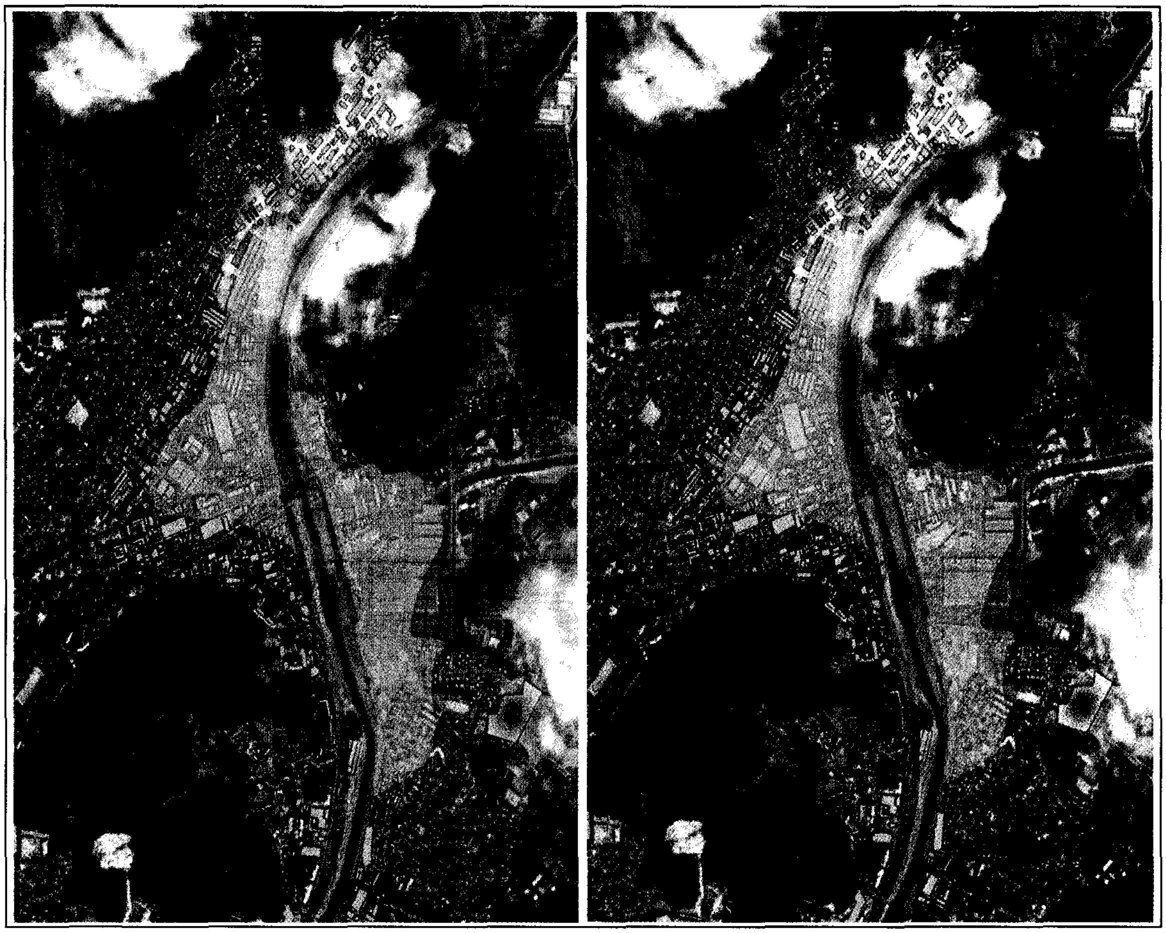


Figure 4-19. Suyoung floodplain mapping: 200-yr flood with no levee (left) vs. levee (right)

4.3.5 Summary and discussion

The Suyoung River in Pusan was chosen to demonstrate the model implementation for delineating a flood inundation area. Hydrological and topographical databases were integrated with the flood inundation simulation model to estimate the flood damage in this chapter as a first step towards evaluating flood damage reduction alternatives. After careful examination of the different types of DEMs, the method of integrating low resolution DEM data with existing surveyed channel elevation data, has been confirmed to depict inundations more accurately (Tate et al. 2002). GIS, HEC-RAS, and the HEC-GeoRAS model were combined to estimate inundation caused by flooding within cross-section No. 57.5 ~ 97.6 in the Suyoung River. Assigning the calculated water surface elevations to the adjusted DEM in the GIS environment allowed a flood inundation map to be determined, which was then converted into a polygon which can be used to generate one of the criteria maps for the next step (Crampton and Fleming 2005). With the comparison described in sections 4.3.3 through 4.3.4, both simulated and observed 1991 Gradys flood events were analyzed and compared. In addition, a comparison of adjusted and unadjusted land terrain DEM's demonstrated the effectiveness of modifying a low accuracy land terrain DEM into a high accuracy adjusted DEM. The adjusted DEM met the qualifications of FEMA's technical standards for base mapping. The analyzed results were displayed as two- or three-dimensional maps, a format which makes it easier for decision makers recognize flooded area.

Although the discrepancies of performances between the simulated and observed 1991 Gradys flood extent were not perfectly correct, the simulation results are still accurate enough to use as a base map for delineating potential flooded area. The results shown in this chapter will help in making better and more efficient flood inundation maps that will in turn influence the results of an MCDA. The next step of this research is to make a GIS-based MCDA interactive model for better, more transparent, and quicker decision analysis.

4.4 A GIS-based MCDA interactive model description

In order to evaluate the alternatives, an MCDA interactive model containing all of the decision parameters was developed. Matlab software was chosen to implement the MCDA methods. This developed model incorporates user-supplied conditions. The user can select the DEM resolution, resource criteria, alternatives, flood frequencies of interest, relative importances, normalized weights, degree of optimism, best and worst values, results lists, and more. The Matlab coding for four different MCDA techniques was internally incorporated to calculate every criteria value for an area. The user interface was programmed with Matlab software as well. Using the developed GIS-based MCDA interactive model, one can easily calculate results using a deterministic (crisp) approach as well as a spatial fuzzy approach for any given data set.

The methodology described in this research was used for the development of a GIS-based MCDA interactive model that:

- Is linked to GIS coverage for data acquisition and spatial analysis, so that the only required user input is the selection of the related data to be evaluated (Shrier 2004);
- Is constructed considering interactivity, transparency, and a good graphical interface permitting the choice of multiple criteria (Gomes and Lins 2002);

- Allows the decision maker to freely examine any part of his or her choice (Gomes and Lins 2002);
- Provides the means to implement the theoretical advances in MCDA in a user friendly system that enables real-time decision making through interactive and iterative procedures, thereby enhancing the decision maker's perception of the problem and influencing his or her judgment and decision making policy (Gale 2006).

The main GUI for this research is shown in Figure 4.20. Within the main GUI, MCDA techniques such as CP, SCP, SFWAM, and ISFWAM can be selected and applied to evaluate candidate alternatives. The caption for each radio button is meaningful enough to be easily understood. For example, if the user chooses the ISFWAM method, the GUI will show the ISFWAM subroutine GUI as shown in Figure 4.21.

The variety of MCDA algorithms compute internally the values for evaluating the alternatives using the user-supplied conditions shown in Figure 4.21. Item 1, DEM resolution, reads the DEM data at the chosen resolution from a user defined file directory. DEM sets have the option of $3m$ by $3m$ and $5m$ by $5m$ grid resolution. In Items 2 and 3, the user can choose multiple criteria for evaluating alternatives. Item 4 presents flood frequency options. Item 5 allows setting the relative importance of the criteria, or the ratio of the importance of each criterion as compared to the least important criteria. The least important criterion has a relative importance factor of 1. The type of rating scale in Item 5 should be selected to fit the user's desires and the characteristics of the problem. For this research a scale of 1 to 100, with 100 representing the best performance, and 1 representing the least performance were selected. Normalized weightings, Item 6, are computed by dividing the relative importance factor for a specific criteria by the sum of the relative importance factors for all criteria (Fontane 2003). Item 7 selects the optimism degree of the user. The value indicates the neutral, optimistic or pessimistic preference of the decision maker (Nirupama and Simonovic 2002). Item 8 shows the distance metric image (values) for chosen alternatives. Using the input boxes in the GUI shown as Item 9, the user can input and modify the parameters required for calculation. At program start, the GUI shows automatically the predefined or imported input parameter from the GIS step (best and worst value, and p value) for each criterion.

After modifying or filling in the user-preferred parameter values, the user can execute the developed model by clicking the 'CALCULATE THE DISTANCE METRIC' command button. After computing the distance metric, the results file is created and saved automatically into a user-defined directory created for ranking of alternatives.

To query the information that is already calculated and saved in the user-defined directory, the user clicks a circle or rectangular shape on the picture control shown as Item 10. This causes highlighting of the selected result name in the List Box Control. The GUI then displays and checks every data item in the condition menu form. It should be noted that user could save the results in the graphic form as a file and also load previously calculated results.

Figure 4.22 represents another sub GUI of alternatives ranking using the CP and SCP approaches. The ranking GUI was developed for displaying the results of the GIS-based MCDA interactive model, and shows the rankings of multiple alternatives. The ranking map displays valuable information. First, it displays the most suitable alternative for flood damage reduction according to the preferences specified. For the CP method, these are the alternatives with respect to their ranking scores. In SCP method, a spectrum bar located on the right side of picture indicates the best alternative number. Second, the user can also see the result information calculated in the prior step by clicking the LOAD command control button on the bottom center of the screen, as shown in Figure 4.22.

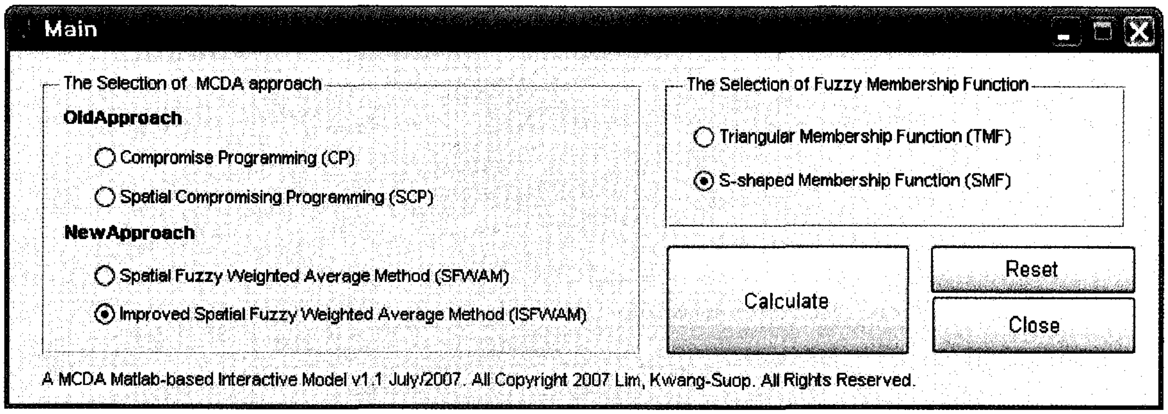


Figure 4-20. The main GUI for MCDA techniques

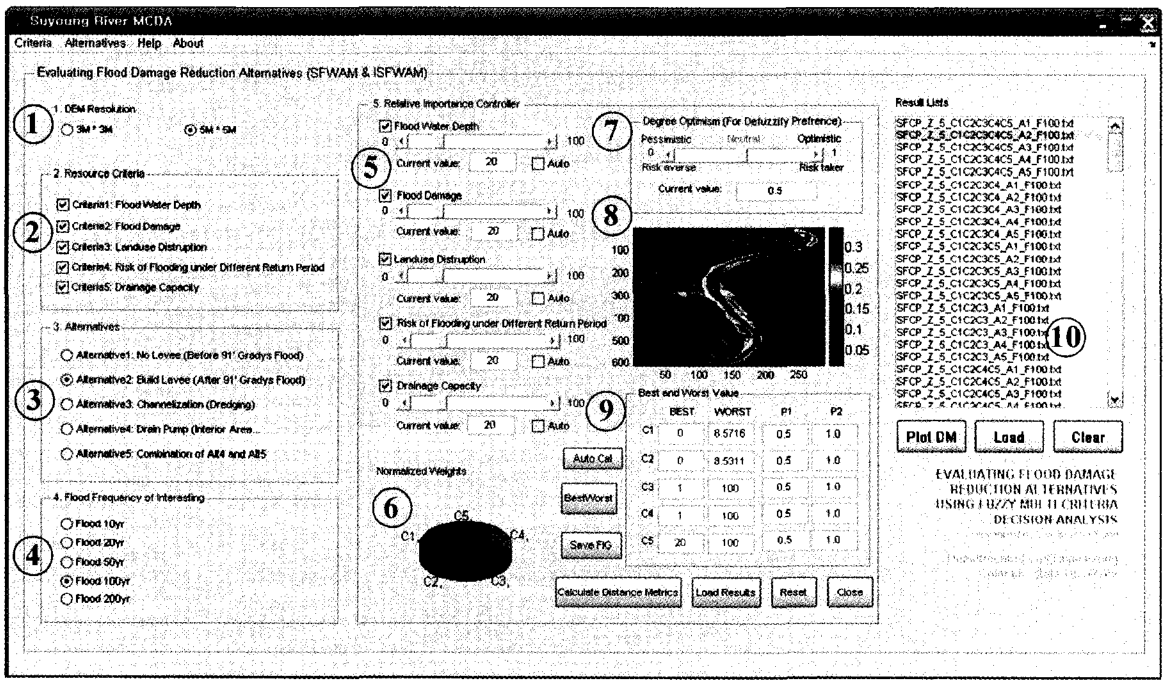


Figure 4-21. A GIS-based MCDA interactive model

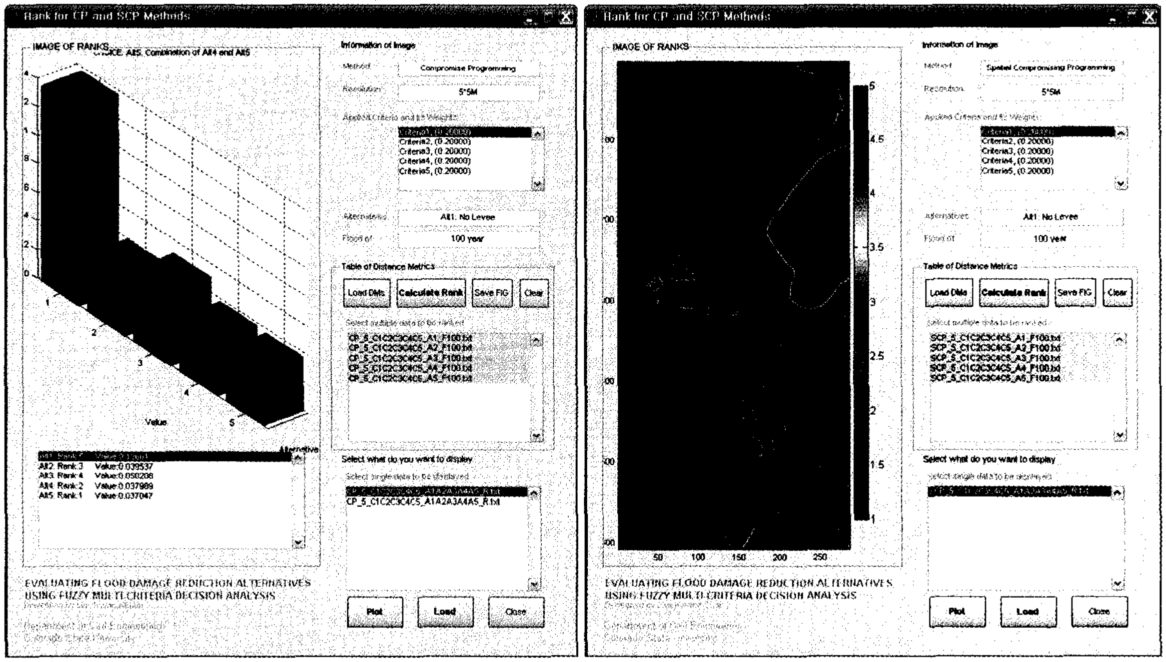


Figure 4-22. Ranking GUI for the CP (left) and SCP (right) techniques

4.5 The deterministic approach to MCDA

Deterministic decision problems assume that the required data and information are known with certainty and that there is a known deterministic relationship (Malczewski 1999) between every decision and the corresponding decision consequence. MCDA methods described in section 3.3.1 and 3.3.2 were applied to evaluate our candidate alternatives.

Broadly speaking, decision-making is a sequence of processes. A multi-criteria decision problem usually involves selection of a number of alternatives to achieve an overall result based on the suitability of those alternatives against a set of criteria. The criteria will normally be weighted in terms of their importance to the decision maker, since criteria are rarely of equal importance. When a suitable process is applied to the problem, a rating of the alternatives can be formed into a rank, based on preferences (Kenevissi 2007). MCDA problems involve a sequence of activities that are based upon the following steps: (1) start with a set of main criteria to be considered; (2) determine the relative importance of each criterion with respect to each other; (3) assign normalized importance weights; (4) select the alternatives to consider; (5) define a common rating scale and convert the scores for the alternatives into ratings; (6) use an MCDA technique to rank the alternatives; and (7) end with a recommendation based upon the ranking of each alternative (Fontane 2003; Malczewski 1999; Simonovic 2002; Tkach and Simonovic 1997). Figure 4.23 illustrates the framework for the deterministic approach to MCDA (CP or SCP) as a part of this research. The details of each step are described below.

To execute a GIS-based MCDA interactive model using a deterministic approach, the decision maker needs to input his or her opinion and set relative importance factors for the main criteria. The relative importance rating scale for each criterion was set to the range of 1 to 100 for this research. After a relative importance value is obtained for each criterion, then the next stage was to establish a set of weights for each criterion by dividing the individual relative importance values by the summation of all the relative importance values. The total of all weights must sum to 1.

The preferences of decision makers are typically expressed in terms of the weights of relative importance assigned to the evaluation criteria under consideration. The derivation of weights is a central step of the evaluation and decision process. For this study, the weighting process was performed from six perspectives.

The first five perspectives each favor either flood water depth, flood damage, land use disruption, risk of flooding under different return periods or drainage capacity. The sixth scenario weights each of the fifth main criteria equally to represent a balanced emphasis (District 2002). The GIS-based MCDA interactive model then calculates the ranking of each alternative based upon an evaluation using the weight of the five main criteria relative to each other. Table 4.9 shows the weighting factors of the related criteria used in each of the six perspectives.

The next step is to select the alternatives to consider. It is necessary to convert the alternative score evaluations to a common numerical score called a 'rating'. A commonly used scale is 1 to 5, where 5 represent the best (most desirable) condition and 1 represents the worst (least desirable) condition. However, in this research various scales were used. As a final step, a recommendation from the decision maker is required, and this step should be based upon the ranking of alternatives as produced by the GIS-based MCDA interactive model. It may involve the description of the best alternative or group of alternatives that are considered candidates for implementation. The model's user interface is of major importance in presenting and communicating the results to decision makers (Thinh and Hedel 2004). Table 4.3 shows the scales that were used in this research. The ratings among alternatives must be combined into a final score for each alternative by an MCDA technique such as CP, or SCP for this section. The CP and SCP methods use the exponent p value (in Equation 3.1 and 3.2) which is used to put increasing stress on the better rating values (Fontane 2003). In this case study, a single value of 2 is used during the evaluation of all alternatives as the value of parameter p (Fontane 2003; Nirupama and Simonovic 2002).

Table 4-9. Weightings of main criteria used in each of the six perspectives

Criteria	Perspectives of main criteria out of a possible 100 points (weighting sets)					
	Emphasize Flood depth	Emphasize Flood damage	Emphasize Land use disruption	Emphasize Flood risk zone	Emphasize Drainage capacity	Balanced Emphasis
Flood depth	[redacted]	10	10	10	10	[redacted]
Flood damage	10	[redacted]	10	10	10	[redacted]
Land use disruption	10	10	[redacted]	10	10	[redacted]
Flood risk zone	10	10	10	[redacted]	10	[redacted]
Drainage capacity	10	10	10	10	[redacted]	[redacted]

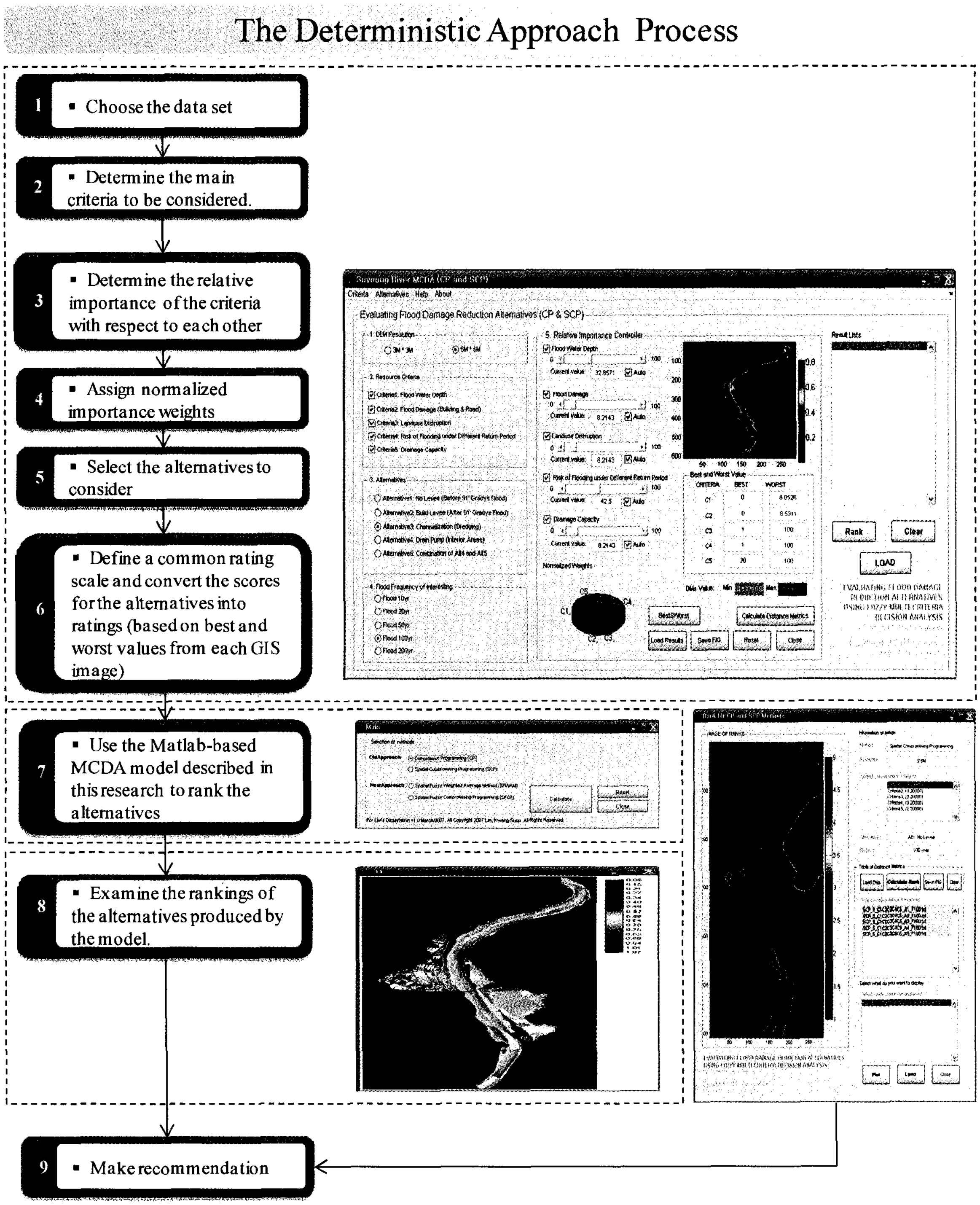


Figure 4-23. The framework for the deterministic approach to MCDA

4.5.1 Compromising Programming (CP) analysis

This section describes the evaluation of all alternatives with six perspectives (weighting sets) for each of the main criteria as shown in Table 4.9. The CP technique is first utilized to identify the most acceptable alternative for the whole Suyoung region. Since the CP method does not take into account spatial variability of the criteria values, the values contained within the criteria images had to be calculated for each of the five criteria into an averaged result for the entire area, representing the impact of each flood damage reduction alternative (Tkach and Simonovic 1997). A GIS-based MCDA interactive model and ranking GUI for the CP technique is shown in Figure 4.24.

Based upon the criteria images and the decision maker's preferences, a distance metric is produced for each alternative. Distance metric values and rankings for the alternatives 'No Levee', 'Levee', 'Channelization', 'Pumping' and 'Combination' for various weighting sets are shown in Table 4.10.

4.5.2 Spatial Compromise Programming (SCP) analysis

The CP method helps in evaluating and ranking alternatives based upon criteria values associated with each of the alternatives, and upon the preferences of the various decision makers. However, the flood management alternatives exhibit spatial variability, in this case, dependence of suitability upon location. Because of the methodological limitations of the CP method, an SCP method was developed which can be used throughout the entire region to incorporate spatial variability. The SCP method evolved from the original work of Zeleny (1973), and includes spatial variability in criteria values to produce a more spatially distributed result (Simonovic 2002; Tkach and Simonovic

1997; Yanar and Akyurek 2004).

It is essentially the same procedure as the CP method with the exception that it makes it possible to discriminate and determine whether some alternatives are better in particular spatial areas. An image identifying the most acceptable alternative for each location in the region for each set of weight is produced. All resulting images then need to be ranked in order to choose the best alternative. The resulting final images contain a distance metric value for each grid cell that corresponds to the relative impact of each alternative. The best alternative for each location is identified by comparing the distance metric values corresponding to the five potential alternatives. Figure 4.25 shows a GIS-based MCDA interactive model and ranking GUI for the SCP technique. Figures 4.26 and 4.27 illustrate distance metric maps for different weighting sets. Figure 4.28 shows the ranked images of different weighting sets. The percentage of the ranked alternatives 'No Levee', 'Levee', 'Channelization', 'Pumping' and 'Combination' for various weighting sets are shown in Table 4.11. This percentage is based upon the relative area where each alternative is the most suitable.

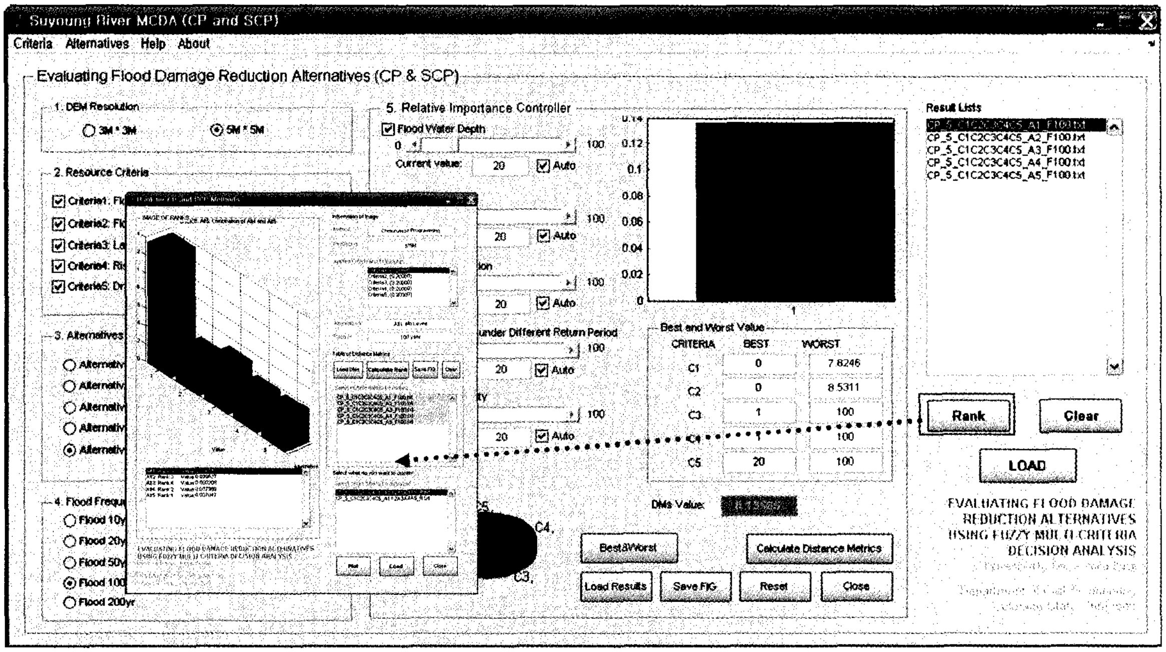


Figure 4-24. A GIS-based MCDA interactive model and ranking GUI for the CP method

Table 4-10. Distance metric value results from the CP method

Alternative	Distance metric value of each alternative					
	Weight Set #1	Weight Set #2	Weight Set #3	Weight Set #4	Weight Set #5	Weight Set #6
1	[redacted]	0.06948	0.06962	0.06943	0.06943	[redacted]
2	0.06955	[redacted]	0.06943	0.06962	0.06962	0.69427
3	0.06948	0.06955	[redacted]	0.06955	0.06948	0.69543
4	0.06954	0.06962	0.06948	[redacted]	0.06954	0.69479
5	0.06943	0.06954	0.06955	0.06954	[redacted]	0.69546

※ Based upon the 100-yr design flood simulation result

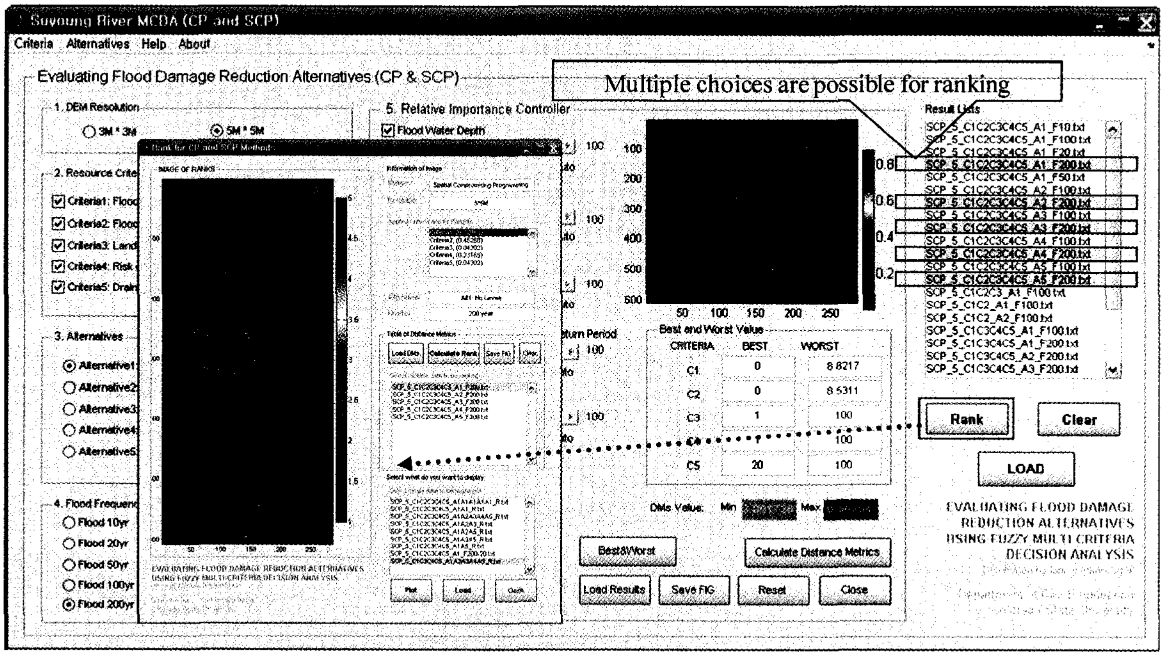


Figure 4-25. A GIS-based MCDA interactive model and ranking GUI for the SCP method

Table 4-11. The percentage locations where an alternative was preferred for various weighting sets

Alternative	Percentage of locations					
	Weight Set #1	Weight Set #2	Weight Set #3	Weight Set #4	Weight Set #5	Weight Set #6
1	83.49%	66.06%	84.29%	90.40%	72.21%	73.66%
2	7.39%	5.44%	7.24%	5.35%	19.06%	9.06%
3	2.36%	1.73%	2.01%	1.82%	2.79%	1.71%
4	2.34%	1.55%	2.45%	1.53%	2.45%	13.53%
5	4.42%	25.22%	4.01%	0.90%	3.49%	2.03%

※ Based upon the 100-yr design flood simulation result

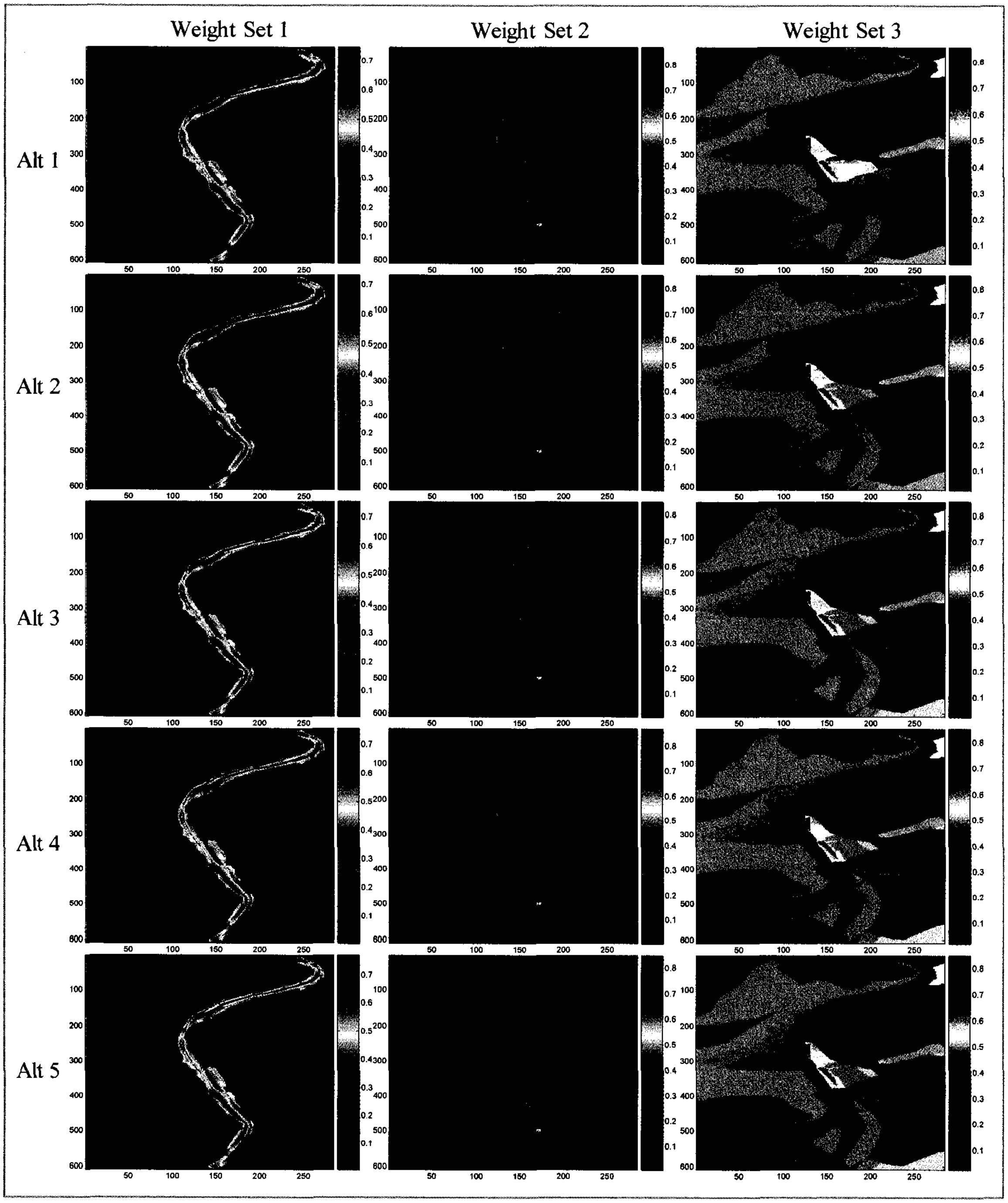


Figure 4-26. Distance metric maps resulting from the SCP method, for weight sets 1 ~ 3

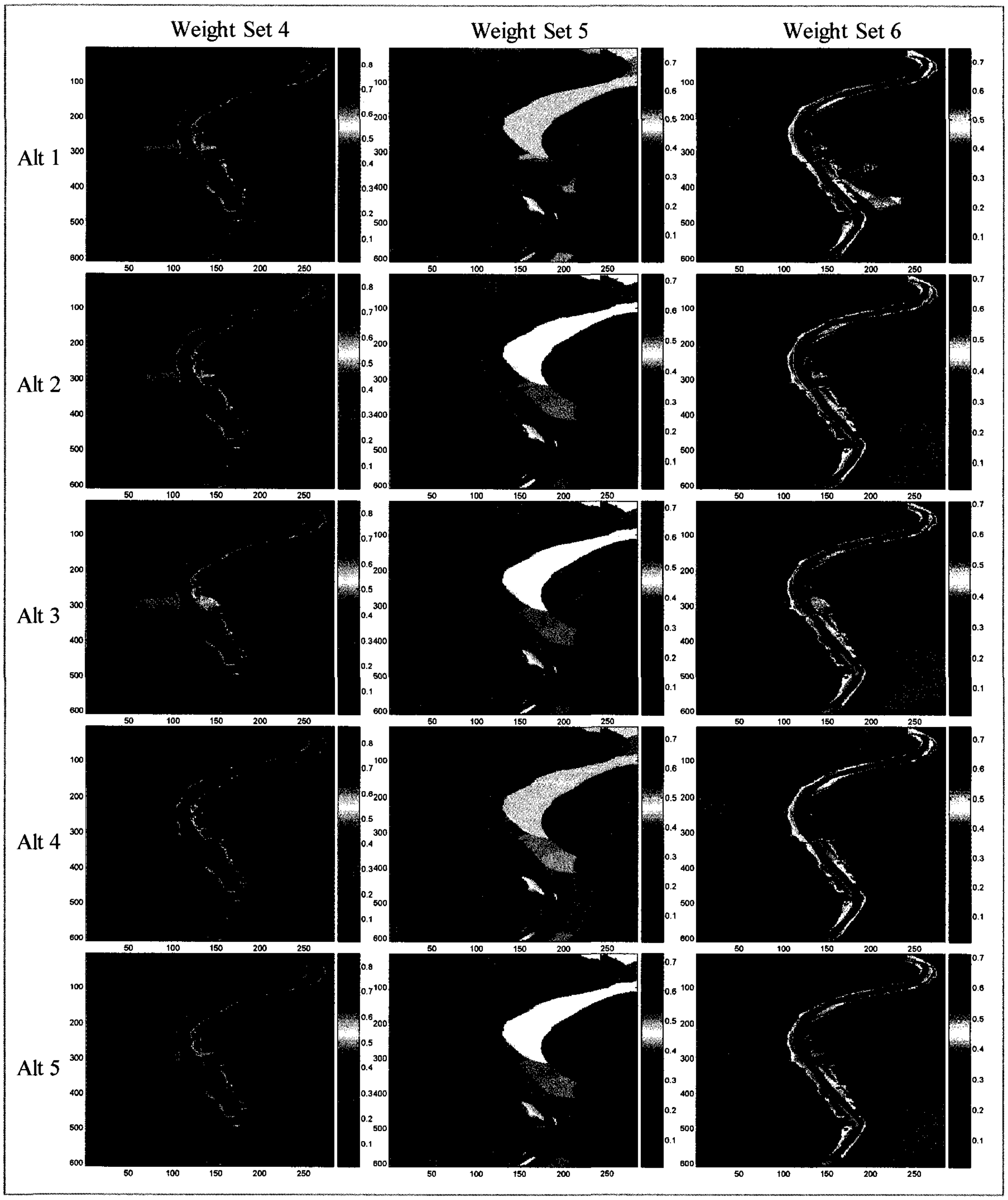


Figure 4-27. Distance metric maps resulting from the SCP method, for weight sets 4 ~ 6

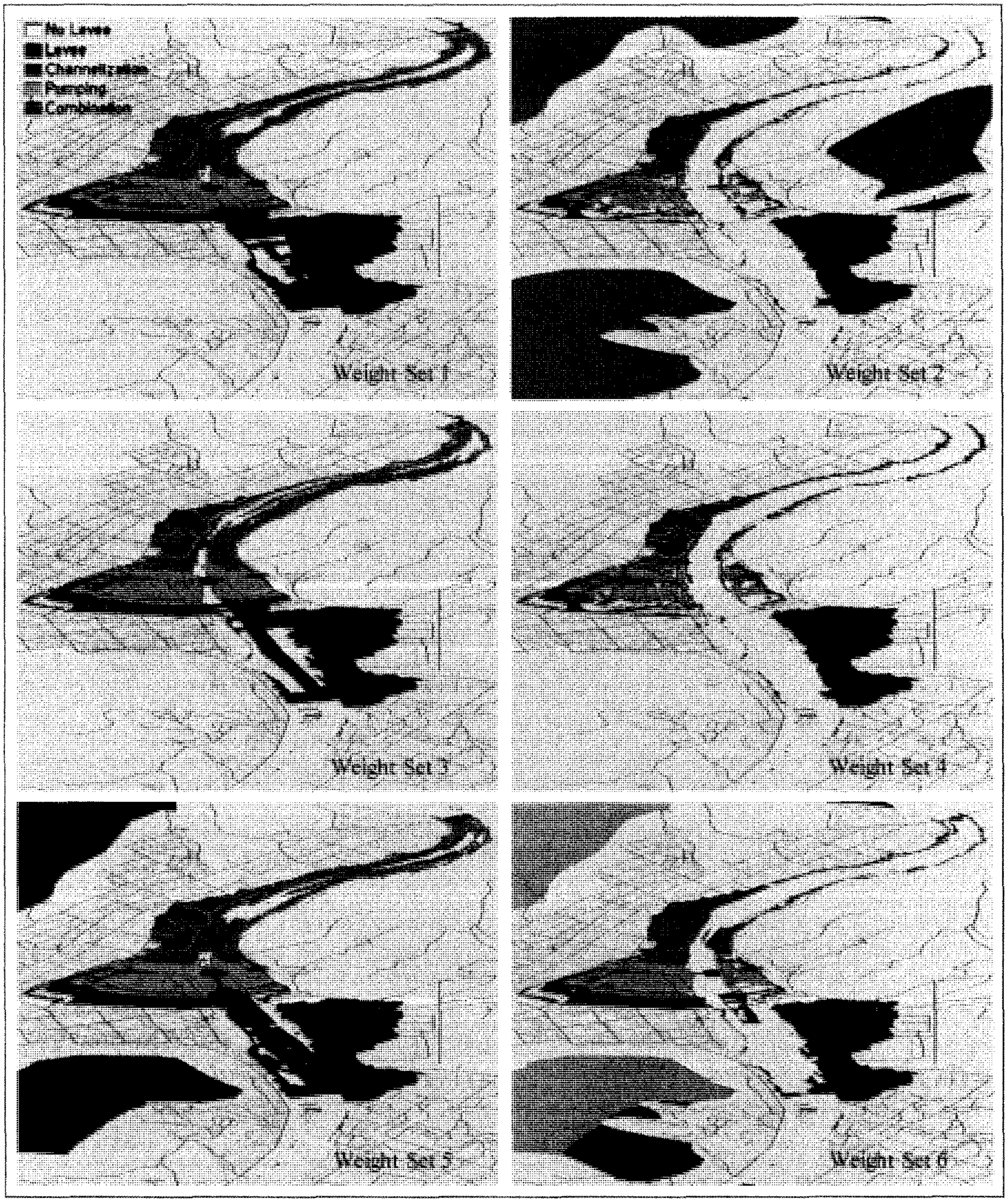


Figure 4-28. Preferred alternatives at each spatial location resulting from the SCP method, for weight sets 1 ~ 6

4.6 The spatial fuzzy approach to MCDA

In an MCDA incorporating multiple decision maker's problems, the evaluation criteria may not be precisely defined. In addition, when the decision makers evaluate the weightings of criteria and the appropriateness of alternatives versus criteria, they usually depend on their wisdom, experience, professional knowledge and information that are difficult to define and/or describe exactly (Liang and Ding 2005).

The uncertainty or imprecision associated with vague parameters and weighting sets, reduces the ability to decide what alternative is better for a particular location. To efficiently reduce the effect of imprecision frequently arising in available information, fuzzy theory has been used to improve consideration of imprecision in an MCDA problem.

As mentioned earlier in section 4.5, the deterministic approach to MCDA does not capture the imprecision, vagueness and imprecision of the data. In deterministic MCDA, the data are treated as if they are precise. Fuzzy logic offers a way to represent and handle imprecision present in continuous real world applications (section 3.4). Extending GIS with fuzzy set theory on the different geographical locations assists the GIS user in making decisions by allowing the incorporation of the user's experiences in the decision-making process. A GIS implementing fuzzy set theory, (referred to in this research as the "spatial fuzzy approach") enables decision makers to express imprecise concepts associated with geographic data and provides decision makers the ability to have even more definition and discrimination in terms of the best alternatives for a particular spatial location.

Following the successful implementation of the deterministic approach for evaluating candidate alternatives, the main objective in this section was to create another extension of the deterministic approach by using fuzzy algorithms to handle imprecision (Thinh and Hedel 2004) and to see whether more criteria will produce more or less diversity of selected options. Nirupama, and Simonovic, S. S. (2002) propose an approach that transforms distance metrics into a fuzzy set by changing all inputs from crisp to fuzzy and applying the fuzzy extension principle.

This research uses a similar concept to that suggested by Nirupama, and Simonovic, S. S. (2002) but improves upon it by making a GIS-based MCDA interactive model. The capability of using a GIS-based MCDA interactive model for the spatial fuzzy approach permits the decision maker to more easily access and determine optimal flood damage reduction alternatives.

Figure 4.29 illustrates the framework for the spatial fuzzy approach (SFWAM and ISFWAM) used as a part of this research. Details of each step are described below. First, the distance metrics are calculated by fuzzification of the criteria images. Each criterion used for calculating distance metrics can be weighted based upon the criterion's importance to the decision maker (Table 4.9). The minimum of this distance is zero, and the maximum is one. Next, the set of all calculated distance metric values is transformed into an S-shaped or triangular membership function to account for imprecision associated with criteria values, weights and the parameters (Nirupama and Simonovic 2002) based upon principles of fuzzy set theory as described in section 3.4. S-shaped and triangular membership functions are illustrated in Figure 3.7.

To efficiently grasp the representation and comprehension of the decision maker's opinions, and the imprecision existing in available information, the algebraic operations of fuzzy numbers, based upon the concept of the α-cut (Liang and Ding 2005), are utilized to find the final aggregation ratings of all feasible alternatives. After the calculation of all membership functions, the spatial fuzzy approach is completed by defuzzifying in order to get a crisp value that best represents a fuzzy set (Nirupama and Simonovic 2002; Thinh and Hedel 2004). In this study, the method of Overall Existence Ranking Index (OERI) (Chang and Lee, 1994), which is based upon a 'centroid of area' method, has been applied for defuzzification of fuzzified distance metrics. The choice of this method is supported by a study done by Prodanovic and Simonovic (2001), which concluded that the OERI method is advantageous with respect to the other methods (Nirupama and Simonovic 2002). Details of the OERI method can be found in Nirupama and Simonovic (2002).

Defuzzified distance metric maps of each criterion were standardized to a common numeric range before ranking the alternatives. The standardization and ranking process was performed by the IDRISI program.

For the described methodology, a GIS-based MCDA interactive model for the spatial fuzzy approach was developed. Using the developed model, a set of MCDA solutions as well as GIS solutions can be created for the evaluation of flood damage reduction alternatives. Moreover, it can be used to make decisions discriminating the scores of the alternatives using fuzzy set methodology. Thus, several alternatives can be generated for decision support.

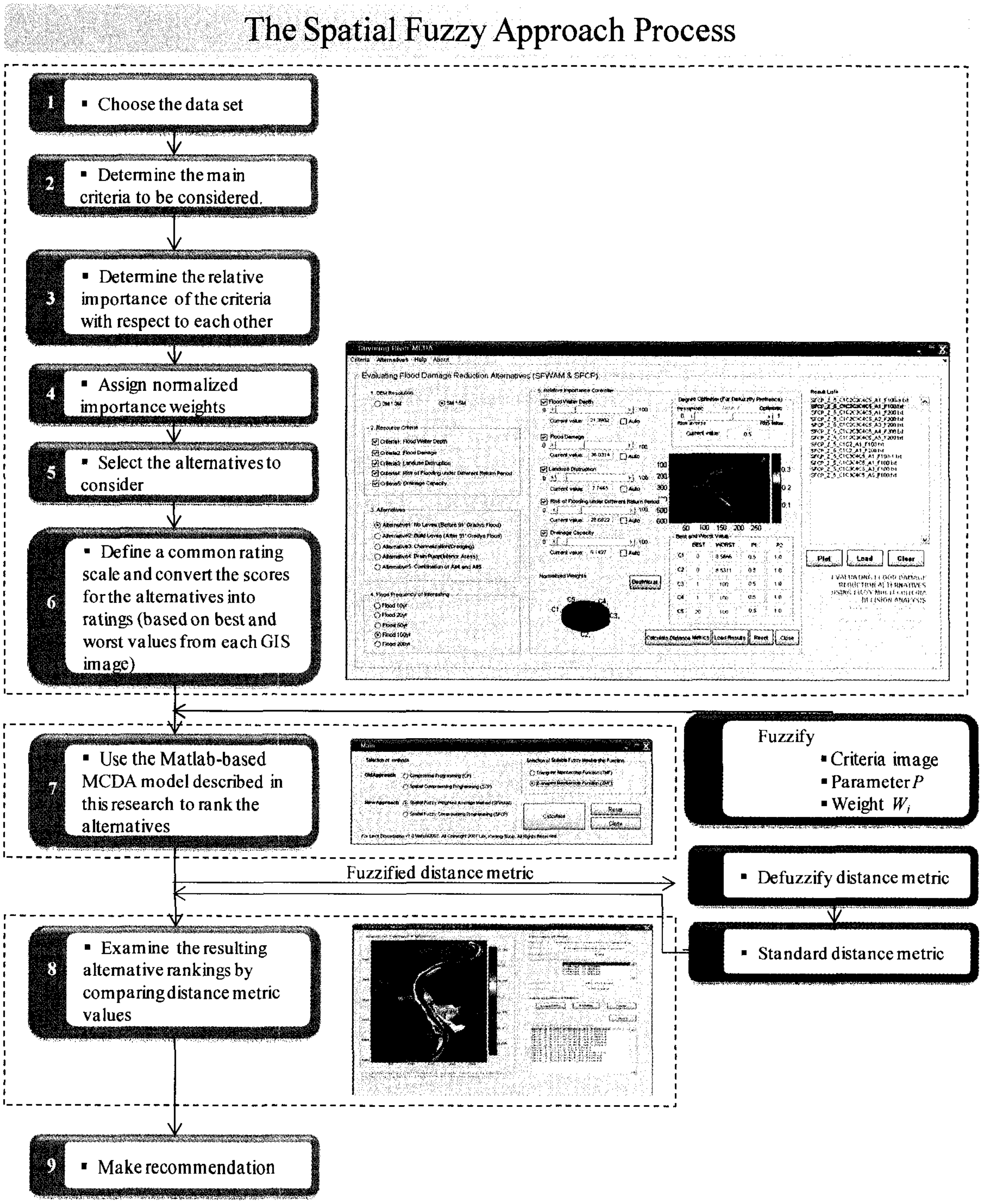


Figure 4-29. The framework for the spatial fuzzy approach to MCDA

4.6.1 Spatial Fuzzy Weighted Average Method (SFWAM) analysis

This section describes the evaluation of all previously defined floodplain alternatives with six perspectives (weighting sets) for the main criteria, as shown in Table 4.9. The SCP technique helps in evaluation and ranking of the alternatives based upon the criteria values associated with each of the alternatives and preferences of the various decision makers. Although flood management alternatives exhibit uncertainty or imprecision in the spatial data, the spatial fuzzy approach (SFWAM or ISFWAM) can help improve the consideration of the imprecision in the analysis. In addition, it gives more diversity and discrimination of the alternatives.

The SFWAM technique is the first spatial fuzzy approach to be implemented for demonstrating that the incorporation of fuzzy theory into a GIS-based MCDA interactive model for the SFWAM method produces more acceptable results than those from the deterministic approach. The GIS-based MCDA interactive model for the SFWAM was shown in Figure 4.30. The SFWAM method is described in section 3.3.3, and uses both the triangular and S-shaped membership functions that were described in section 3.4.2. The operational procedure of the developed model is same as that mentioned in section 4.6.

4.6.1.1 The Triangular and S-shaped Membership Function

The SFWAM was implemented using a triangular and S-shaped membership function (section 3.4.2). The criteria maps were combined by fuzzy logical operators such as intersection and union in the SFWAM using the triangular and S-shaped membership function (section 3.4.3). As a result, there were a total of 30 georeferenced distance metric maps (for all five alternatives and all six weight sets) for evaluating the alternatives. Figures 4.31 ~ 4.34 are distance metric maps from the list of candidate alternatives and weight sets. Since the main criteria have been developed to reflect the objectives of the flood damage reduction plan, the resulting rankings indicate which alternatives best fulfill these objectives. Figures 4.35 ~ 4.36 contain a map showing the ranking of alternatives for each criterion that could be implemented to meet flood planning objectives.

Note the distance metric maps from the SFWAM-SMF method show generally lower distance metric values in Figure 4.36 over most of the area of interest with respect to the SFWAM-TMF results.

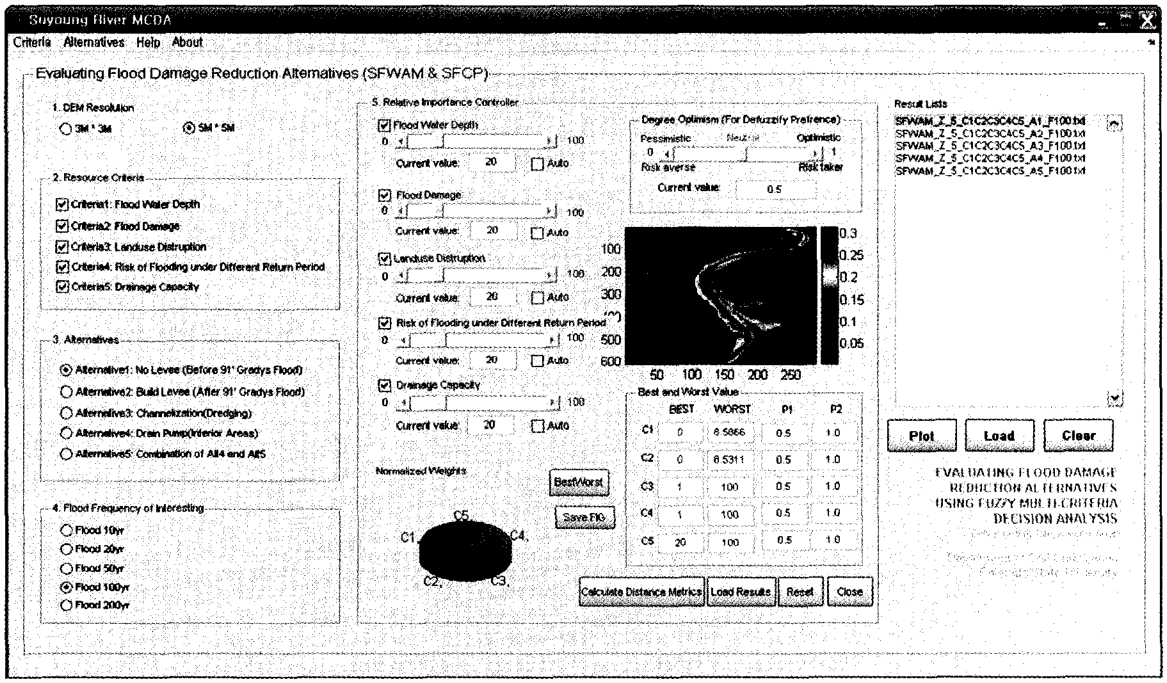


Figure 4-30. A GIS-based MCDA interactive model for the SFWAM method

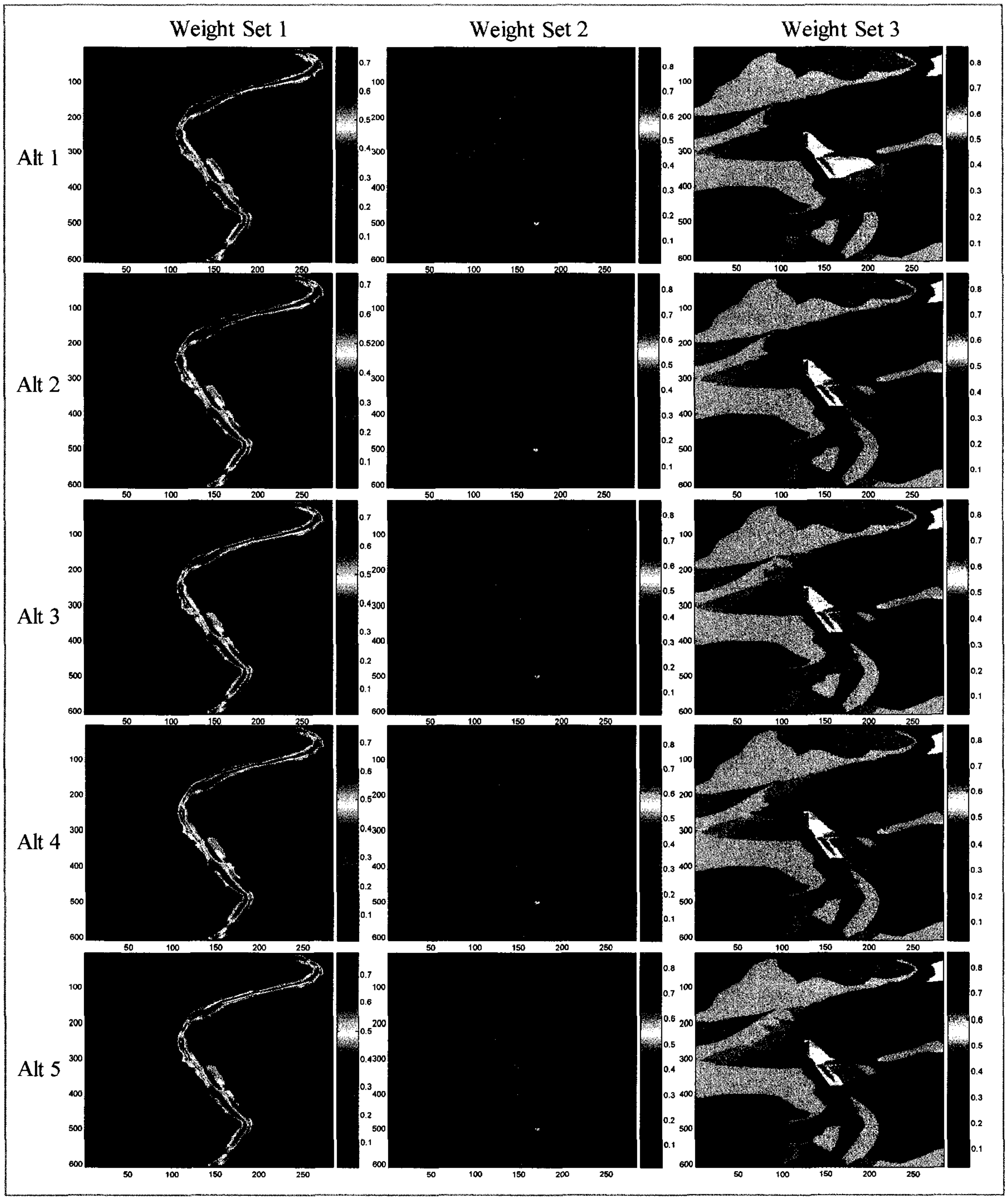


Figure 4-31. Distance metric maps resulting from the SFWAM-TMF method, for weighting sets 1 ~ 3

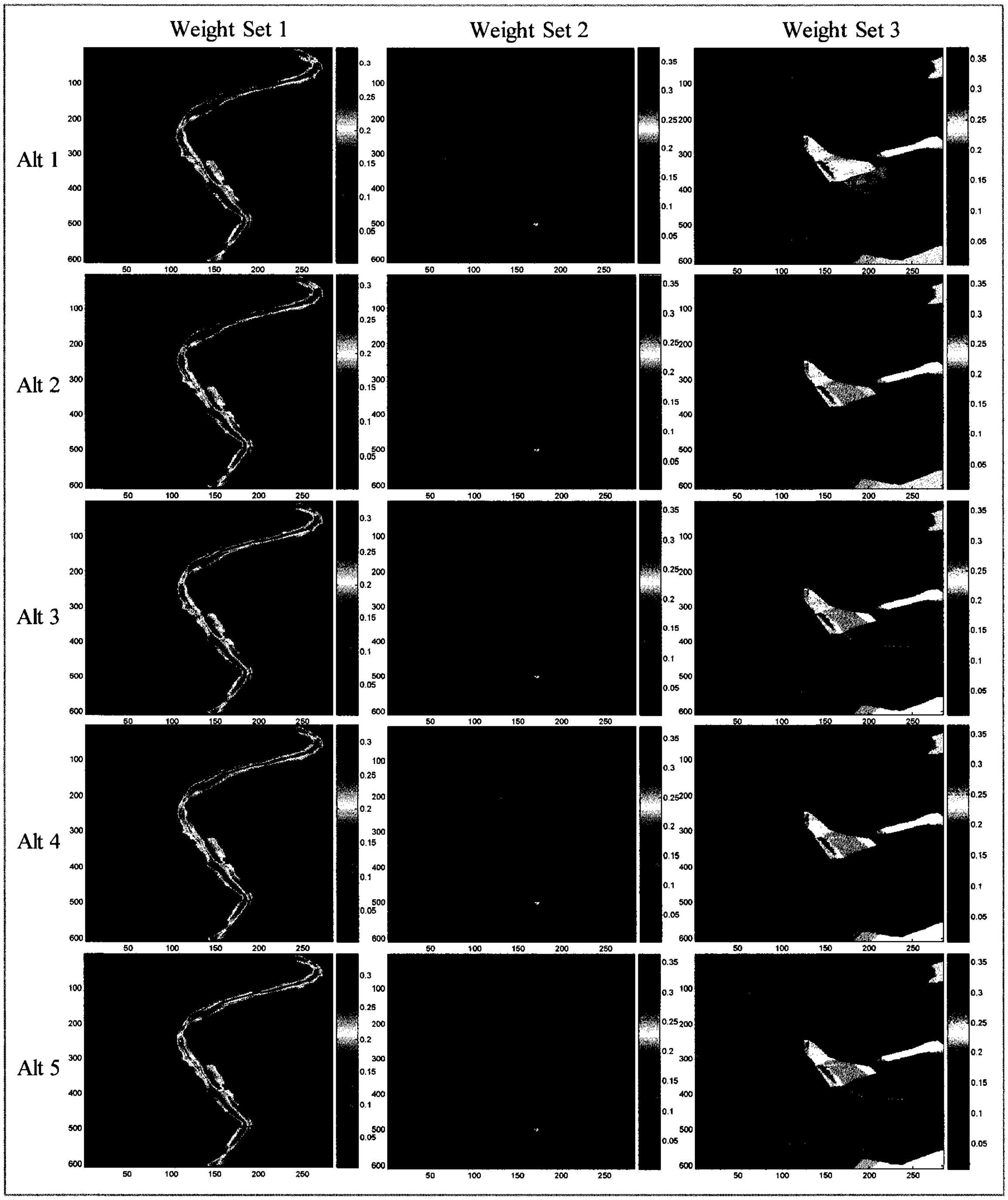


Figure 4-32. Distance metric maps resulting from the SFWAM-TMF method, for weighting sets 4 ~ 6

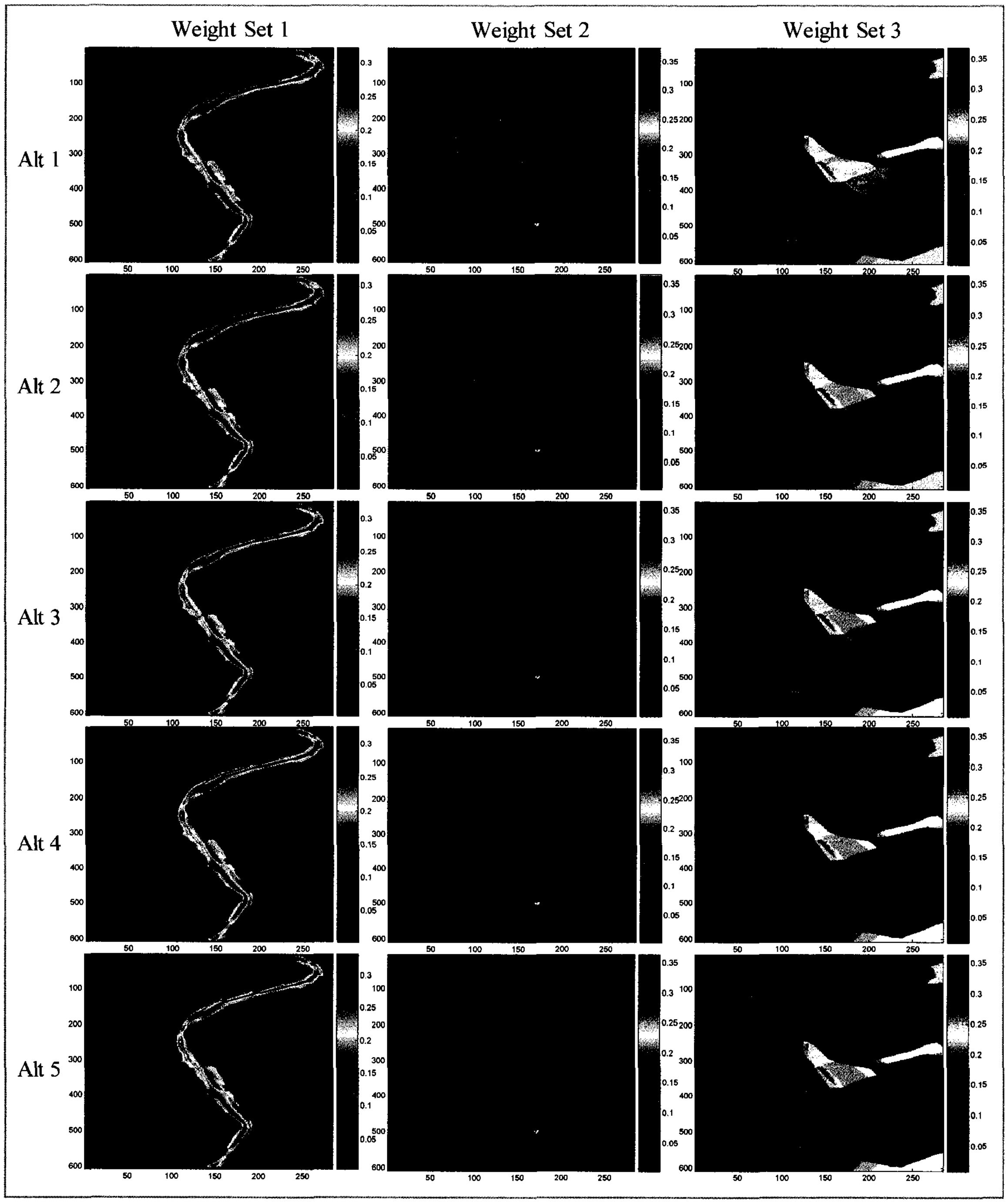


Figure 4-33. Distance metric maps resulting from the SFWAM-SMF method, for weighting sets 1 ~ 3

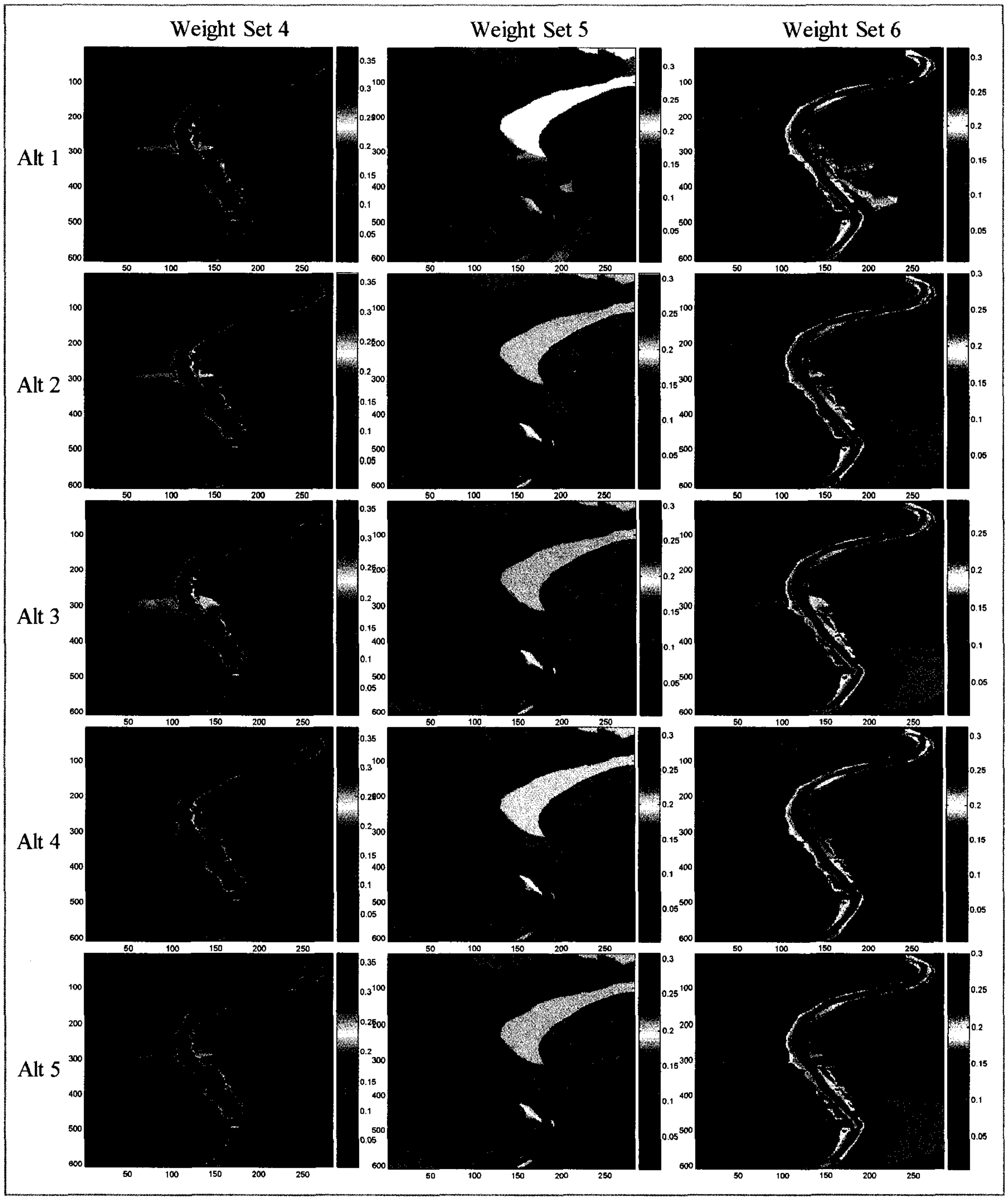


Figure 4-34. Distance metric maps resulting from the SFWAM-SMF method, for weighting sets 4 ~ 6

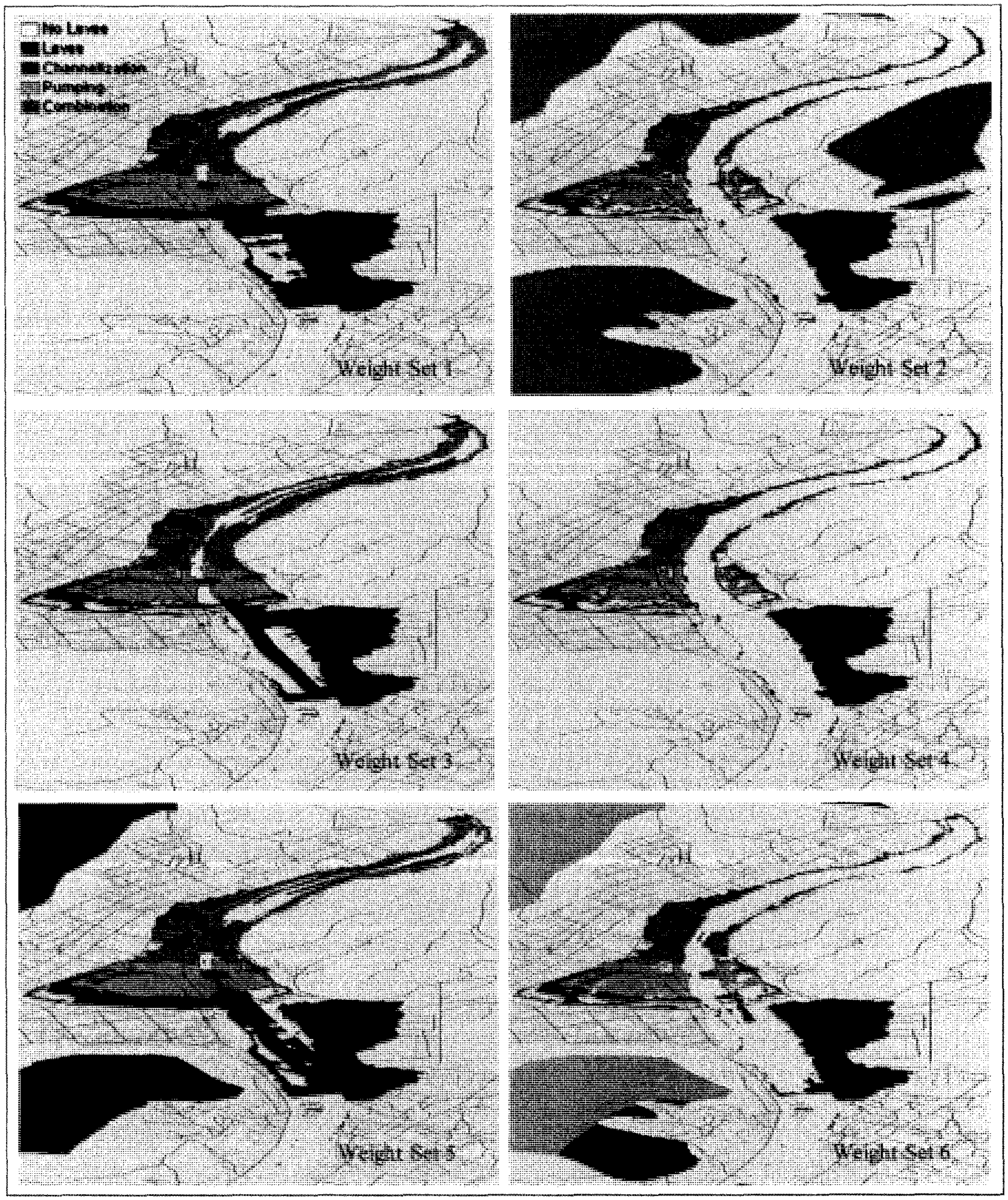


Figure 4-35. Preferred alternatives at each spatial location resulting from the SFWAM-TMF method, for weight sets 1 ~ 6

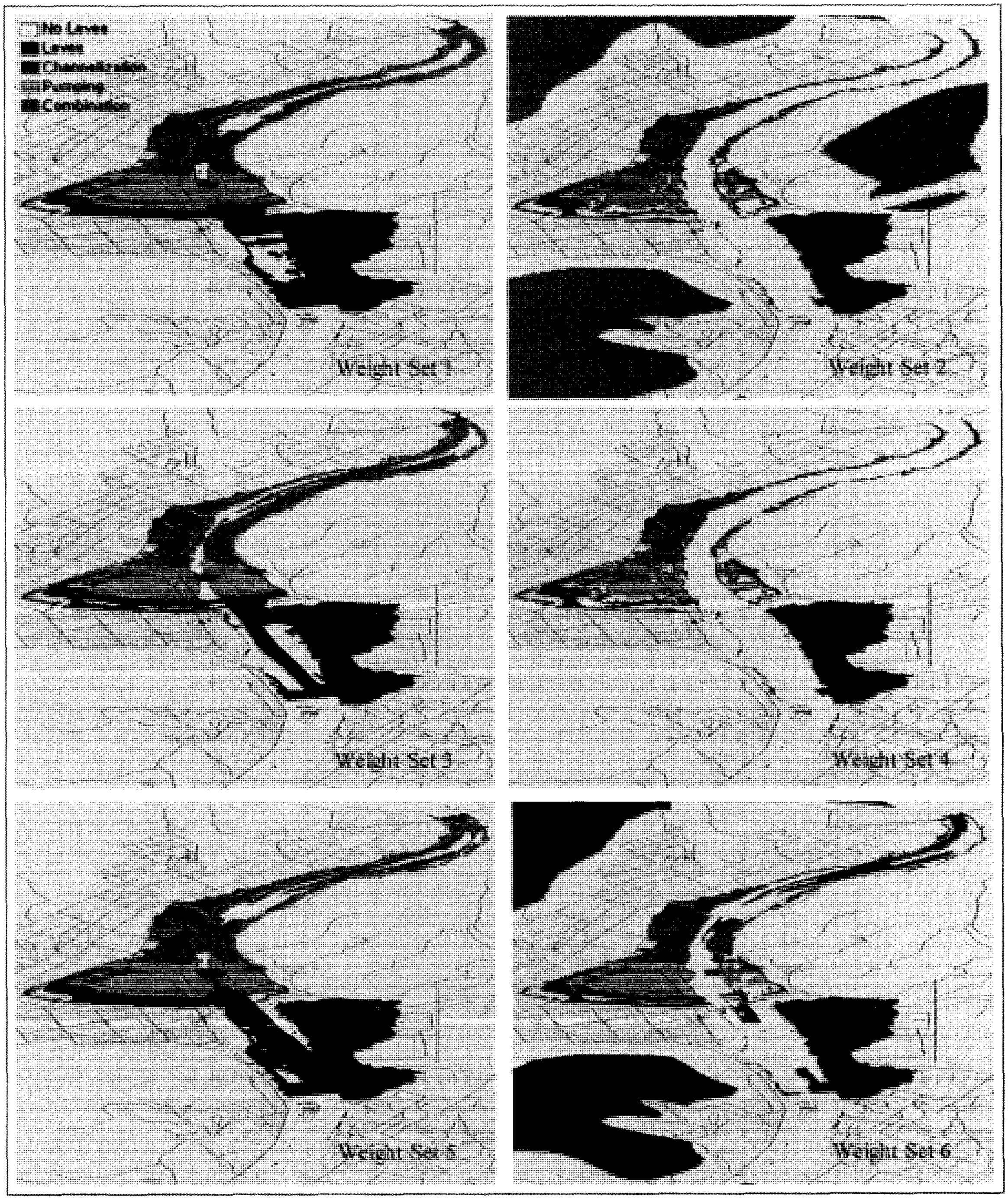


Figure 4-36. Preferred alternatives at each spatial location resulting from the SFWAM-SMF method, for weight sets 1 ~ 6

4.6.2 Improved Spatial Fuzzy Weighted Average Method (ISFWAM) analysis

This section evaluates all the alternatives with six weighting sets for the main criteria, as shown in Table 4.9. It is the same procedure as the SFWAM method except that it considers the parameter p value (sections 3.3.2 and 3.3.4) of each criterion. The ISFWAM technique helps in the evaluation and ranking of alternatives based upon the criteria values associated with each of the alternatives and the preferences of the various decision makers.

The ISFWAM method (section 3.3.4) uses both triangular and S-shaped membership functions (section 3.4.2) and was implemented for the evaluation of flood damage reduction alternatives using a GIS-based MCDA interactive model. The GIS-based MCDA interactive model for the ISFWAM is shown in Figure 4.37. The resulting final images contain a distance metric in each grid cell that corresponds to the relative impact of each alternative. This is shown in the right-hand center of Figure 4.37. The best alternative for each location is identified by comparing the distance metric values corresponding to the five potential alternatives. The IDRISI program was used for ranking purposes. The operational procedure of the developed model is the same as mentioned in section 4.6.

4.6.2.1 The Triangular and S-shaped Membership Function

The ISFWAM using the triangular and S-shaped membership function (section 3.4.2) was executed and distance metric maps were acquired for all six weight sets (Table 4.9). The criterion maps were combined by fuzzy logical operators such as intersection and union in the ISFWAM using the S-shaped membership function. As a result, there were a total of 30 georeferenced distance metric maps (for all five alternatives and all six weight sets) for evaluation of the flood damage reduction alternatives. Figures 4.38 ~ 4.41 are distance metric images from the list of candidate alternatives and weight sets. Since the main criteria has been developed to reflect the objectives of flood damage reduction planning, the resulting rankings indicates which alternatives best fulfill these objectives. Figures 4.42 ~ 4.43 contain a map showing the ranking of alternatives for each criterion that could be implemented to meet flood planning objectives. Note the distance metric maps from the ISFWAM-SMF method show generally lower distance metric values in Figure 4.43 over most of the area of interest with respect to the ISFWAM-TMF results.

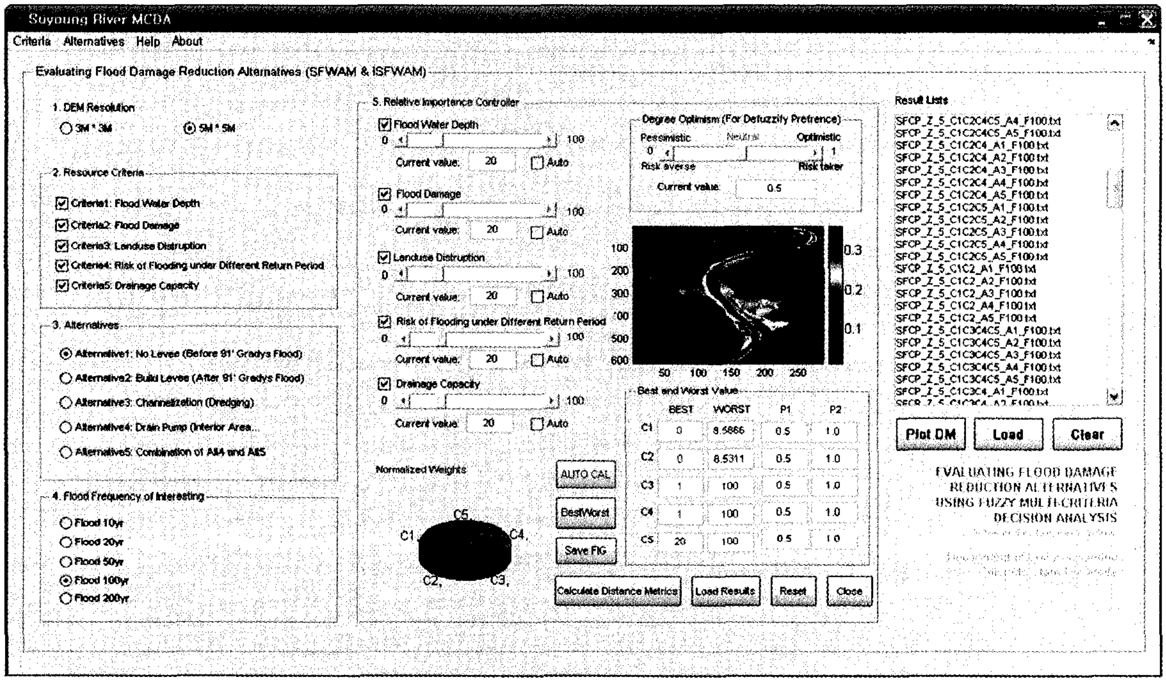


Figure 4-37. A GIS-based MCDA interactive model for the ISFWAM method

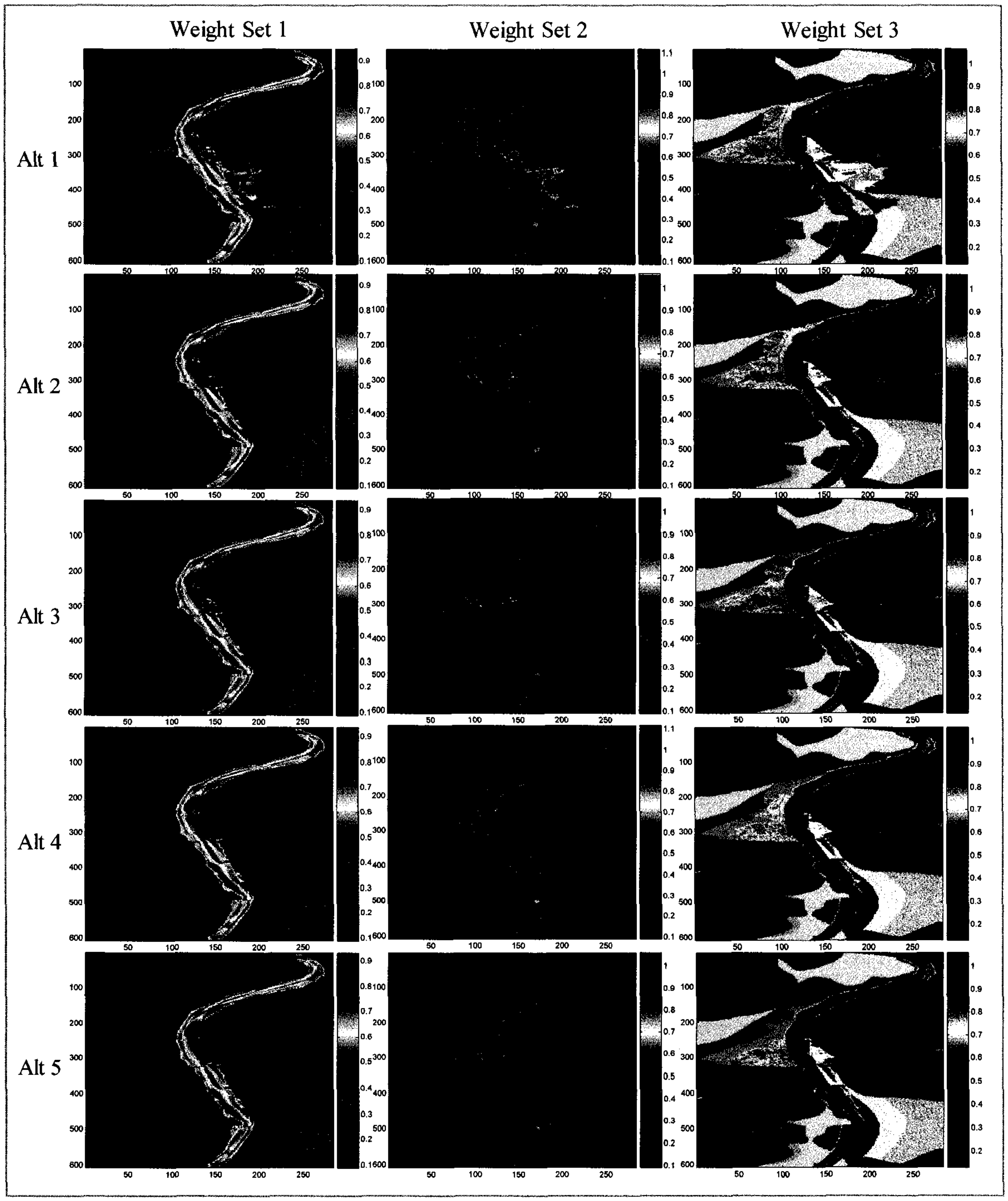


Figure 4-38. Distance metric maps resulting from the ISFWAM-TMF method, for weighting sets 1 ~ 3

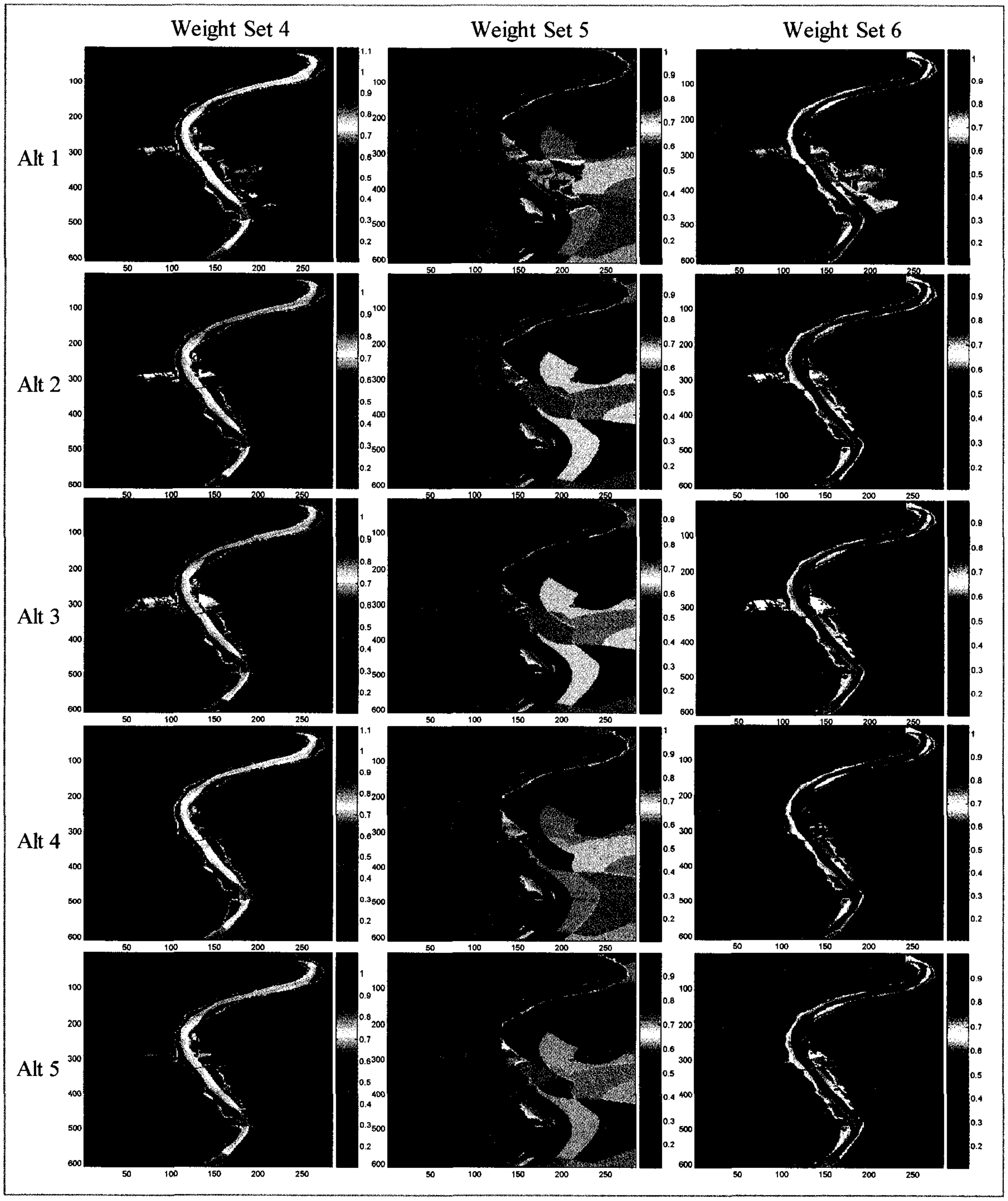


Figure 4-39. Distance metric maps resulting from the ISFWAM-TMF method, for weighting sets 4 ~ 6

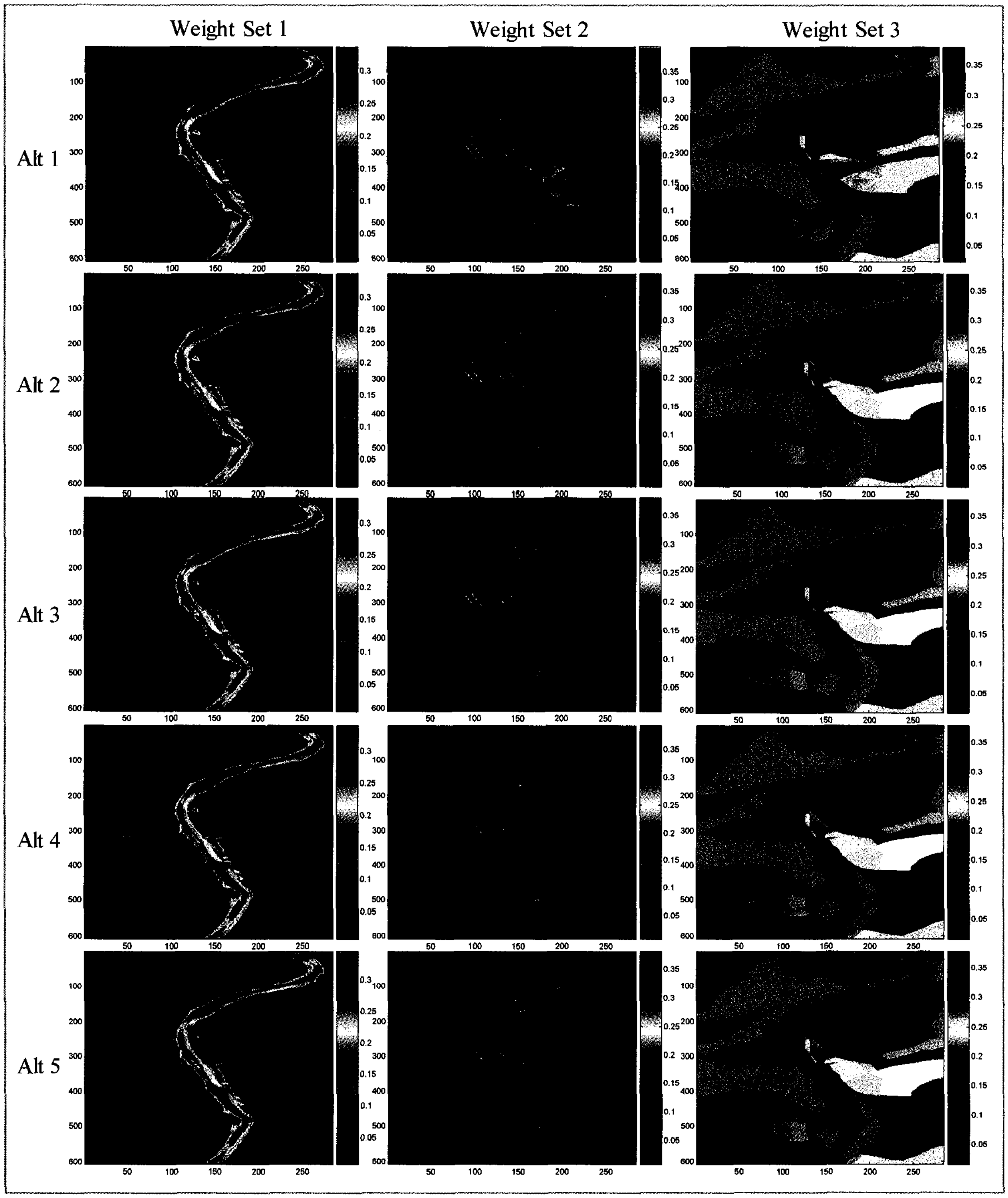


Figure 4-40. Distance metric maps resulting from the ISFWAM-SMF method, for weighting sets 1 ~ 3

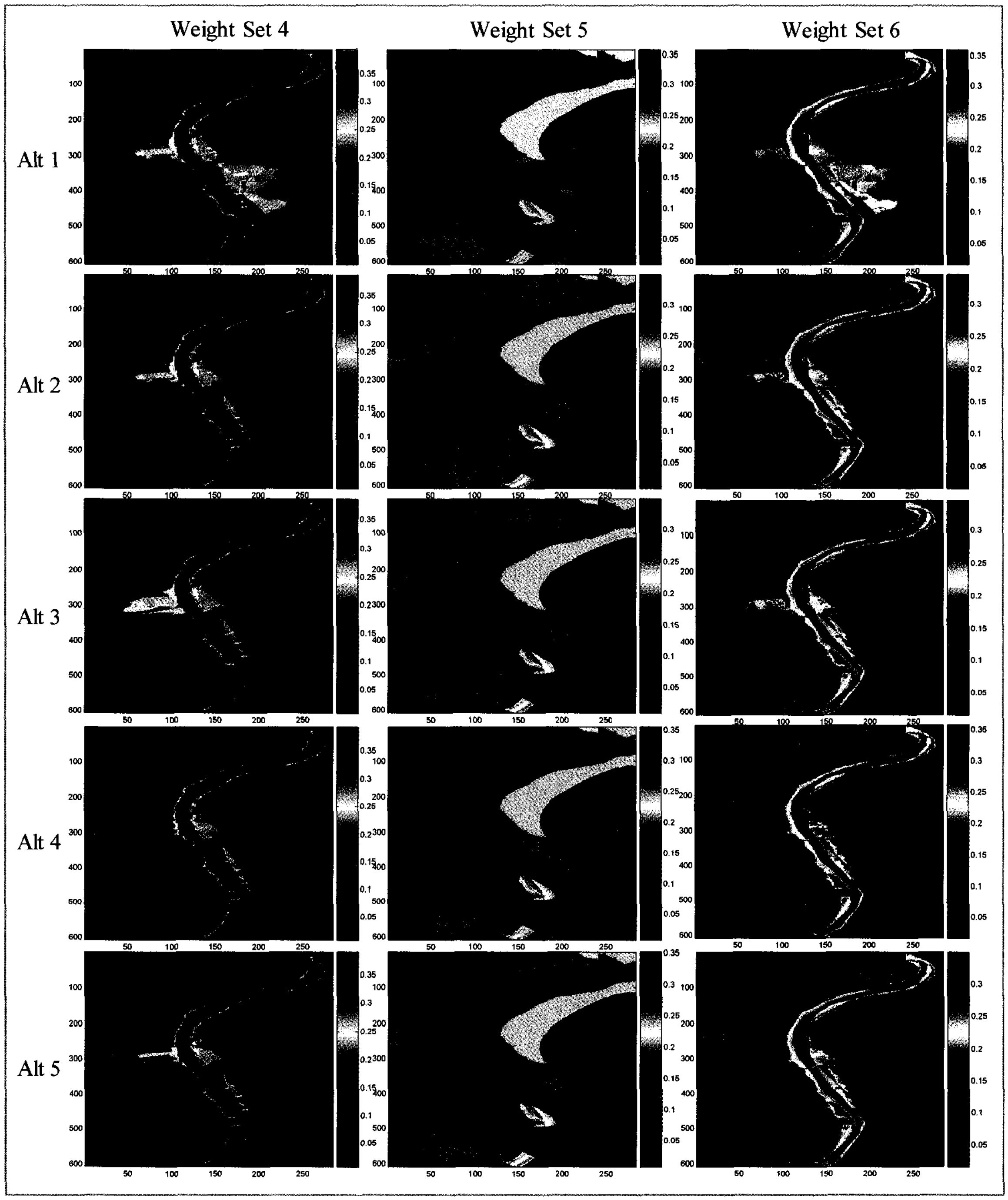


Figure 4-41. Distance metric maps resulting from the ISFWAM-SMF method, for weighting sets 4 ~ 6

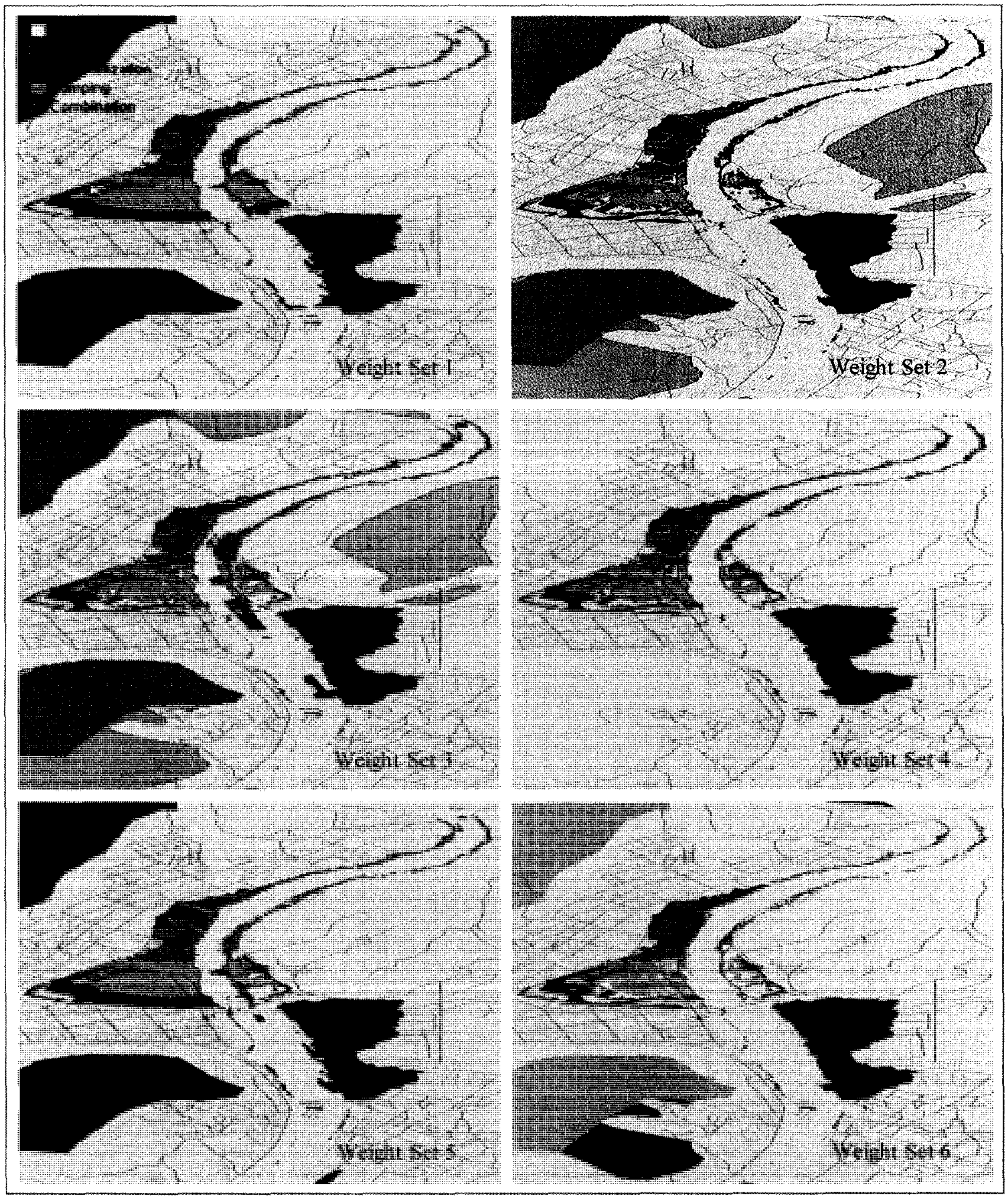


Figure 4-42. Preferred alternatives at each spatial location resulting from the ISFWAM-TMF method, for weight sets 1 ~ 6

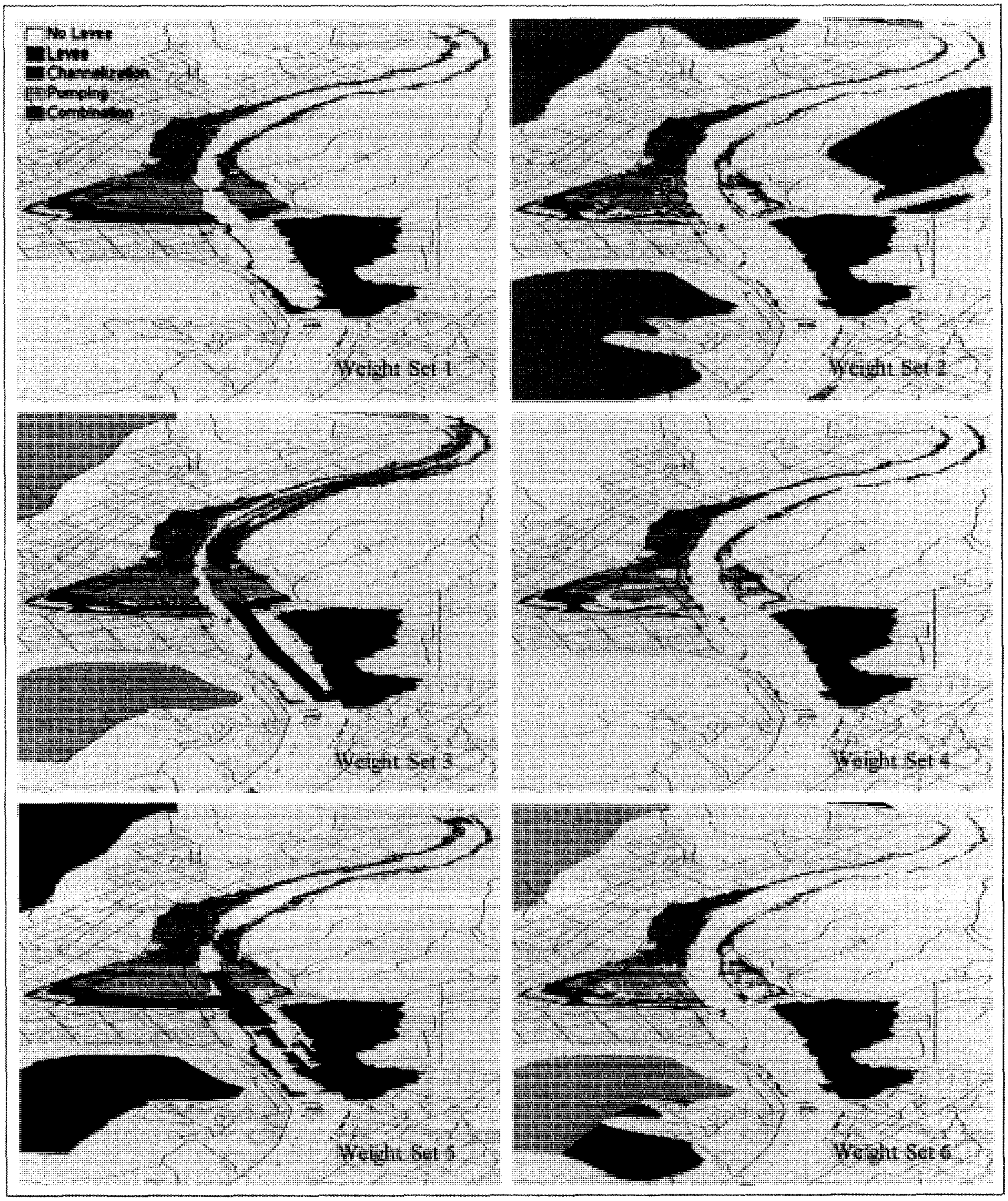


Figure 4-43. Preferred alternatives at each spatial location resulting from the ISFWAM-SMF method, for weight sets 1 ~ 6

4.7 Synthesis of Spatial Results to Recommend a Preferred Alternative

As described in the previous section, the integration of GIS and fuzzy MCDA allows the engineer to determine the preferred alternative for each spatial location in the study area. The next step is to recommend to the final decision makers a single flood management alternative for the entire region. Note that if the study area is large, it might be possible to use the kind of information shown in Figure 4.43 to recommend different alternatives for different portions of the region. However, for this study it is assumed that only a single alternative will be used.

The solution shown in Figure 4.43 represents the best possible solution if each location could have it most preferred answer. This is obviously unachievable; however, the overall sum (or the average) of the distance metrics for all spatial locations represents a lower bound or baseline against which options can be compared. If a single alternative is selected for the entire region, then the average of the distance metrics for all spatial locations will increase. The increase in this average represents a "cost of uniformity" for that alternative. Comparing these "costs of uniformity" for each of the alternatives can give an indication of the relative order of the alternatives in terms of their average scores.

To assist the comparison of the average scores for the alternatives, the increase in average scores was scaled from zero to one, where one corresponds to the largest increase in average score. An example of the calculation of the "cost of uniformity" is shown in Figures 4.44 and 4.45. It is apparent from these figures that selecting Alternative 5 as the entire basin alternative has the smallest increase in the "cost of uniformity." Compared to the baseline condition, selection of Alternative 5 results in an increase of 6% of the average score. If Alternative 4 is applied everywhere, the overall average score increases by 17%. By comparing these increases to the values for selecting the other alternatives (Alternative 3 = 25%, Alternative 2 = 36% and Alternative 1 = 100%) decision makers can see that alternatives 5 and 4 would clearly be the preferred options.

There might be situations where the selection of the alternative might be influenced most heavily by a particular region in the floodplain. To illustrate this situation the Geumsa area in the upstream portion of the Suyoung River Basin was selected as an important area that might influence the selection of the preferred alternative. The Geumsa area is an urban area with government buildings and hospitals. The "cost of uniformity" calculations were made for the Geumsa area only and the results are shown in Figures 4.46 and 4.47. For this particular region only Alternative 5 still has the smallest increase in the "cost of uniformity" and the second choice is still Alternative 4. However, the relative increase in the "cost of uniformity" was larger (Alternative 5 = 47% and Alternative 4 = 55%). This is an indication of the large amount of diversity of the optimal alternative for individual location in this region.

This kind of analysis could be applied to any region of the floodplain as desired. Whether the decision makers decide to apply these calculations to the entire floodplain or to specific important regions within the floodplain, an analysis of the increases in the cost of uniformity provides an integrated way for the decision maker to rank the alternatives. This should provide an improvement in their engineering analysis.

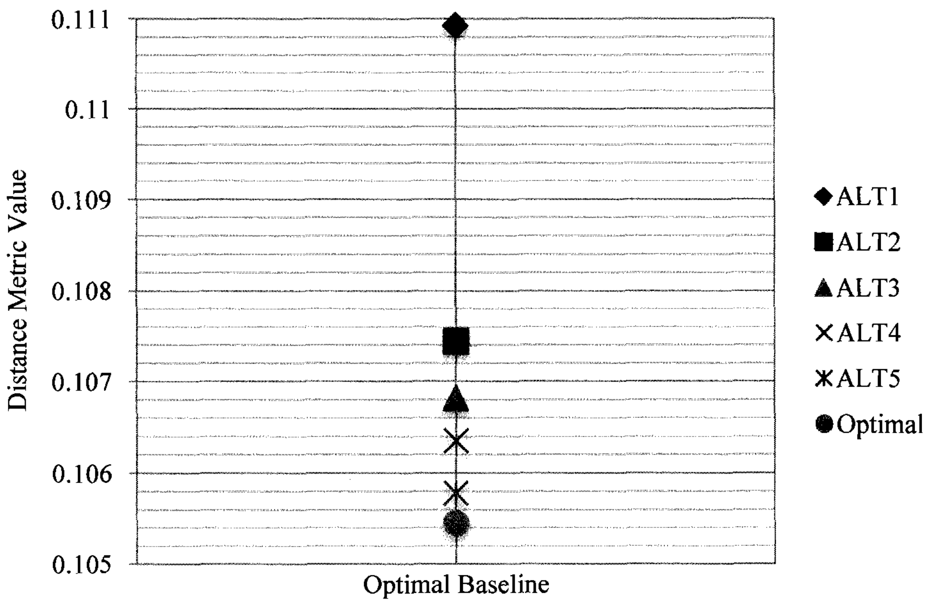


Figure 4-44. The cost of uniformity for each of the alternatives for the entire basin

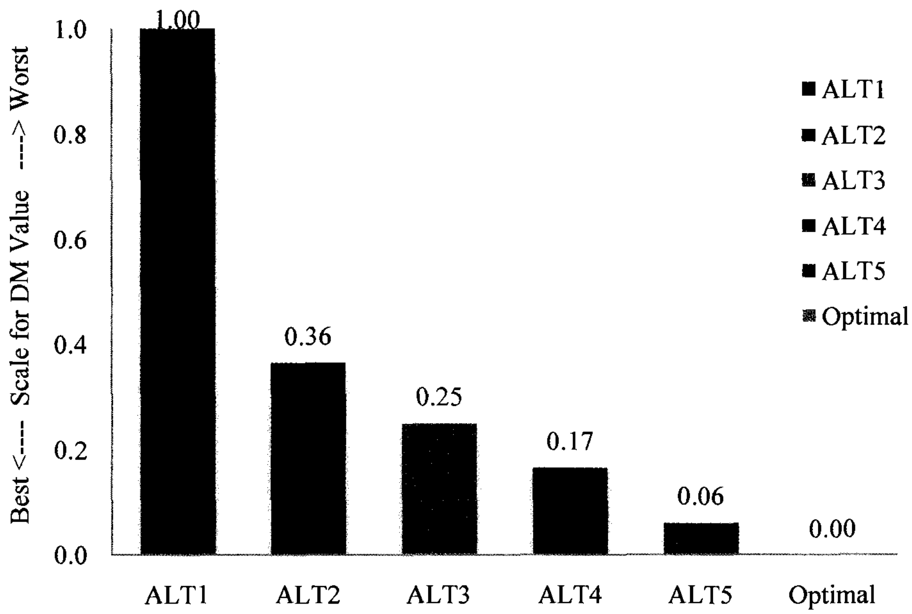


Figure 4-45. Scaling the total distance metric (0 to 1) for the entire basin

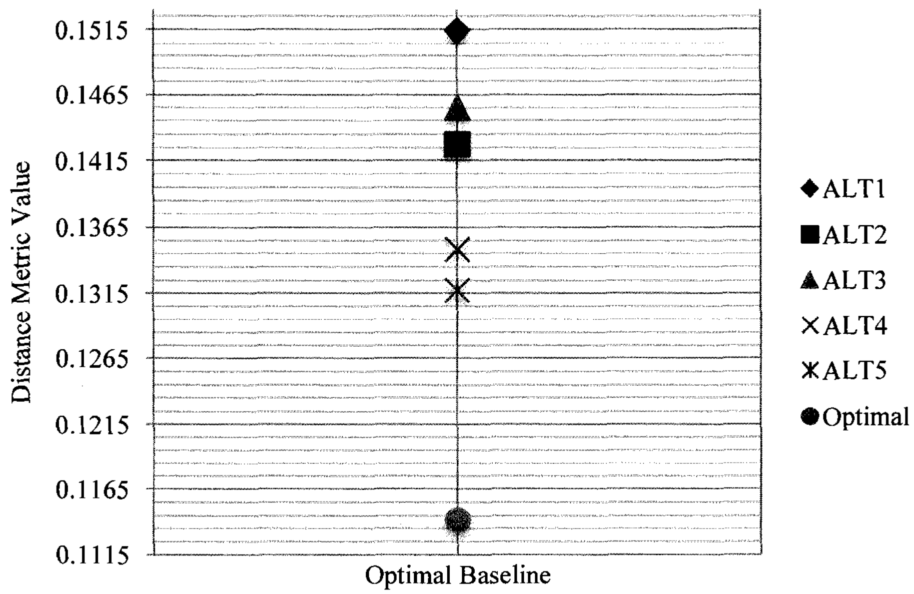


Figure 4-46. The cost of uniformity for each of the alternatives for the Geumsa area

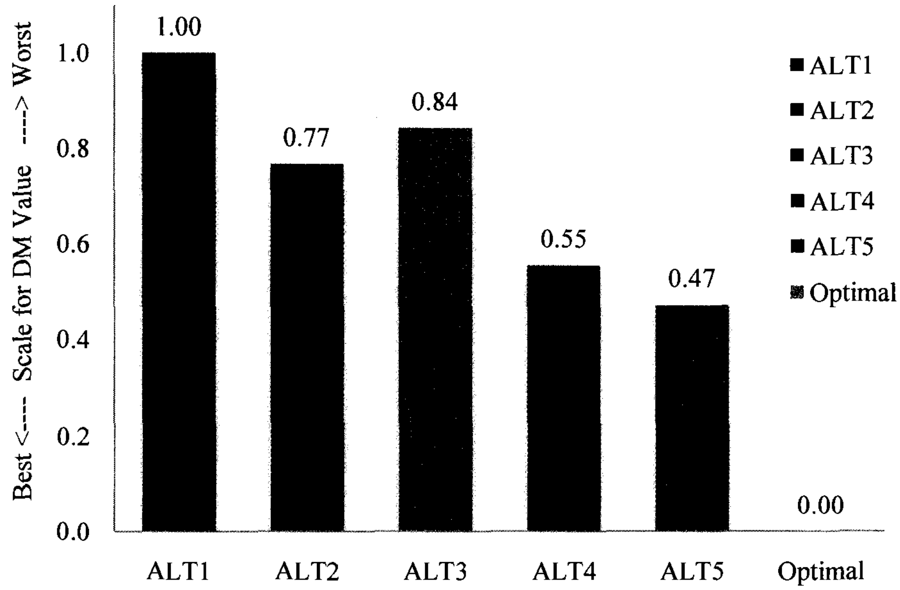


Figure 4-47. Scaling the total distance metric (0 to 1) for the Geumsa area

4.8 Results

This section gives the results of all the experiments performed in this study. Five groups of analyses were arranged according to the implemented MCDA techniques, however in some comparisons only representative results are shown here. For example, comparisons of SCP and ISFWAM-SMF results were representative of the deterministic approach and the spatial fuzzy approach respectively. Using the results illustrated in section 4.5 ~ 4.6, the following comparisons are possible:

1) Comparison of various deterministic MCDA methods;
2) Comparison of various spatial fuzzy MCDA methods;
3) Comparison of deterministic MCDA and spatial fuzzy MCDA;
4) Comparison of adjusted and unadjusted DEM maps using a spatial fuzzy MCDA approach; and
5) The impact of inserting additional criteria into the MCDA.

4.8.1 The deterministic approach in an MCDA context

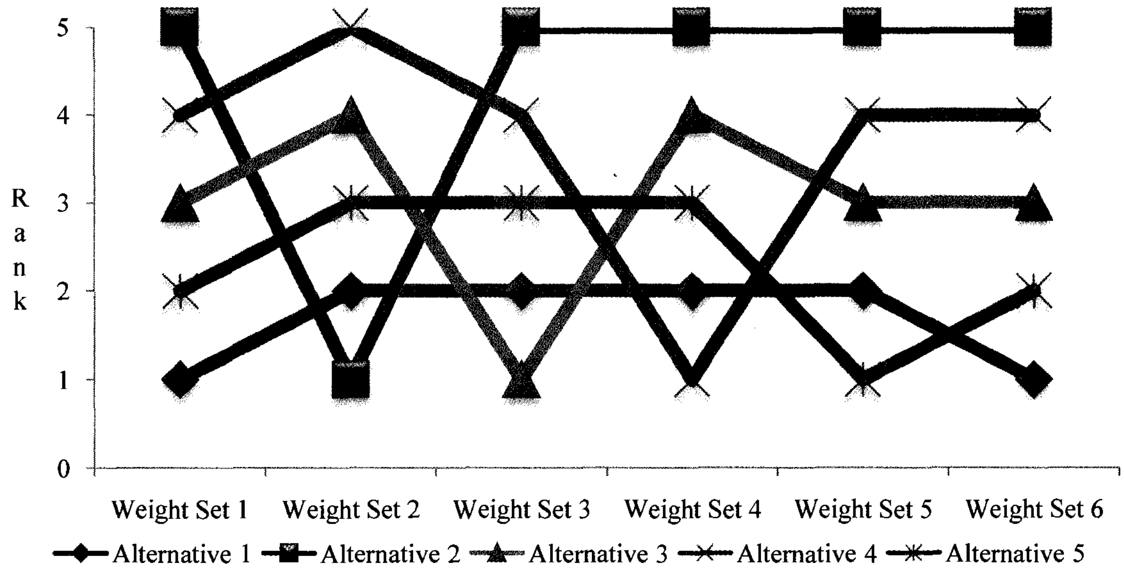
MCDA methods described in section 4.5 were applied to evaluate various flood damage reduction alternatives. Performances of the alternatives were then compared according to the flowcharts in Figure 4.23. First, the CP method was applied to evaluate the alternatives and then the SCP method was applied.

In first method, CP, the highlighted cells in Table 4.10 are those that are the best-ranked floodplain alternatives for each weighting set. The alternative having the smallest distance metric value (Equation (3.1)) is selected as the most appropriate for the entire

Suyoung region. On the other hand, the alternative having the largest value of the distance metric is therefore determined to be the worst alternative (Tkach and Simonovic 1997).

Comparison of both the distance metric value and overall rankings for different weighting sets of all alternatives was performed following the flowcharts in Figure 4.23 resulting in a ranking for each different weighting set. In Figure 4.44, the graph (upper) and the table (lower) shows the overall final rankings for all six possible cases. This simple figure and table gives some valuable information in terms of the decision-making for evaluating floodplain alternatives in the Suyoung area.

Since the rankings depend on the relative weighting given to each of the criteria, the weighting is one of the important parameters that can affect the criteria, as shown in Equation (3.1). The weighting sets were chosen to give emphasis to specific criteria. Weighting set 1, has a large weight for criteria 1 and smaller, equal weights for the other criteria. In a similar manner, weighting set 2 favors the second criteria, and so forth. Weighting set 6 has the criteria equally weighted. For this study, the alternatives have been ranked from the six weighting sets identified in Table 4.9. The results illustrate the problem with the spatial averaging used in the CP method.



Alternative	Weight Set 1	Weight Set 2	Weight Set 3	Weight Set 4	Weight Set 5	Weight Set 6	Average Ranking	Overall Ranking
1	1^{st}	2^{nd}	2^{nd}	2^{nd}	2^{nd}	1^{st}	1.66	1^{st}
2	5^{th}	1^{st}	5^{th}	5^{th}	5^{th}	5^{th}	4.33	5^{th}
3	3^{rd}	4^{th}	1^{st}	4^{th}	3^{rd}	3^{rd}	3.00	3^{rd}
4	4^{th}	5^{th}	4^{th}	1^{st}	4^{th}	4^{th}	3.66	4^{th}
5	2^{nd}	3^{rd}	3^{rd}	3^{rd}	1^{st}	2^{nd}	2.33	2^{nd}

Figure 4-48. The overall final rankings for all six possible cases from CP method

As evident in Figure 4.44, the best floodplain alternative determined for the entire geographical region by the CP technique (Equation (3.1)), which uses average or total flood damage impact incurred across the entire region being considered (Nirupama and Simonovic 2002), can be mis-leading. For example, when criteria 1, flood depth, is emphasized, the CP method selects the No Levee option. This results from the metric being averaged over all cells in the basin. The averaging over the basin gives the impression that this is a good alternative.

Overall, it is obvious that the CP method is not suitable for considering and discriminating the best alternatives for every region of interest, since rankings of suitable alternatives for each specific grid cell considered in calculating the final ranking value cannot be obtained (Yalcin and Akyurek 2004). The point is that the CP method does not allow the decision maker to consider the unique characteristics of each strategy at all points. The loss of spatial variability is one of the critical flaws of the CP method that needs to be addressed. Without accounting for spatial variation of the criteria values, this may result in a considerable amount of missing information.

The main idea of the SCP method is to include the evaluation of spatial components throughout the whole basin. With this method, rather than selecting a single alternative for the whole region of interest, a distance metric is calculated for each location in the region (Nirupama and Simonovic 2002). In addition, SCP may give decision makers the possibility to find more spatially distributed strategies. In order to demonstrate this, Figures 4.26 ~ 4.28 show the various results that considered and implemented spatial variability in the criterion values. These figures show distance metric maps for weighting sets 1~ 6 and the rankings of chosen alternatives for each weighting set respectively. One can quickly notice that the SCP method is spatially variable. Since the SCP method produces a value for each grid cell of the area, spatial maps resulting from SCP show dramatic differences. The ranking of alternatives in each weighting set in the table shows significant differences between the strategies in the Suyoung area. Using this method, it is likely many more options will be selected. In other words, the SCP method gives decision makers the capability to use spatial analysis in more than single strategy, for an entire geographical region and to determine the various alternatives. Different strategies might have an advantage since the different spatial characteristics highlight different points in the floodplain.

Figure 4.45 shows the overall final rankings for all six possible cases from SCP method. The preference order for the areas of interest would be:

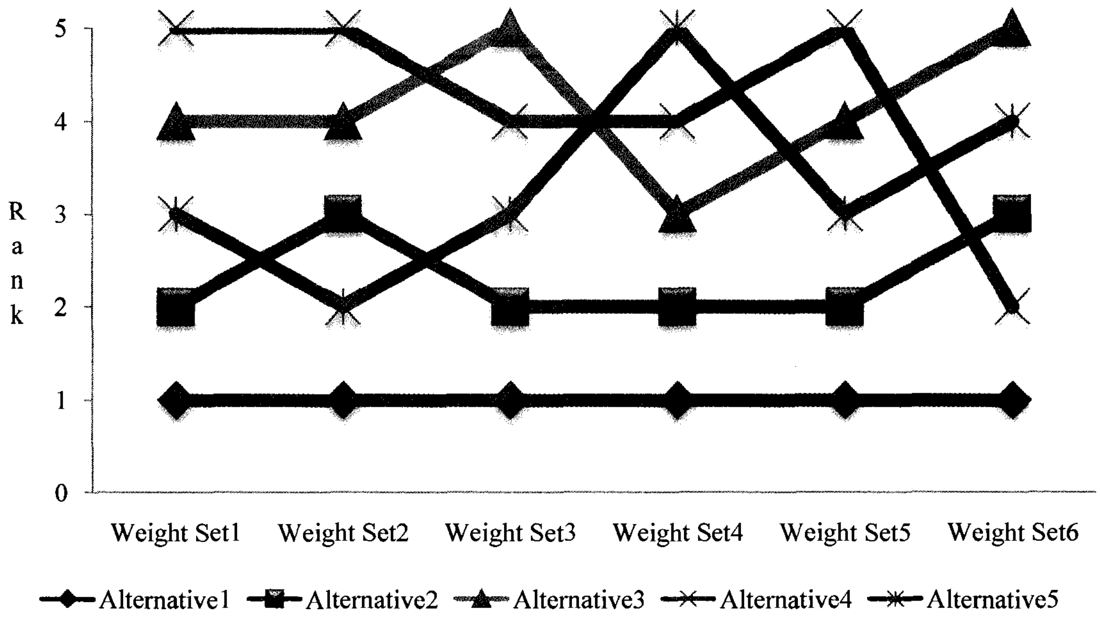
Alternative 1 > Alternative 2 > Alternative 5 > Alternative 3 = Alternative 4

Many of the first-ranked alternatives appearing in the SCP results are Alternative 1 (No Levee). It is important to note the reason why Alternative 1 commands an overwhelming majority with respect to the other alternatives. This occurs because Alternative 1 includes non-flooded area. In other words, there was no action needed for flood protection. Alternative 1 is the only option available for non-flooding areas. Therefore, Alternative 1 will always command a high percentage of grid cells on any map that includes a fair amount of non-flooding area.

In order to have a strict performance comparison between CP and SCP methods, a one-to-one comparison of the results at each grid cell is required. Unfortunately, it is not possible to compare these one-to-one because of the differing format of the results. However, in Figure 4.25, there is a map in the GIS-based MCDA interactive model for

SCP, which indicates the values of the distance metric in each relative region. It is easy to see the differences between the CP and SCP techniques when we compare Figure 4.24 with Figure 4.25. When the ranked alternatives produced by both the SCP method and the CP method are compared, it is found that the SCP method 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 SCP considers distance metric values spatially at each grid cell in the area, whereas the CP method calculates the average value of distance metrics throughout the whole region.

Overall, these comparisons seem to suggest the SCP method is a competitive method for evaluating floodplain alternatives. The SCP method gives abundant information allowing the decision maker to more accurately discriminate among the best alternatives under investigation. The next step of this research is analysis of a spatial fuzzy approach in an MCDA context (SFWAM and ISFWAM).



Alternative	Weight Set 1	Weight Set 2	Weight Set 3	Weight Set 4	Weight Set 5	Weight Set 6	Average Ranking	Overall Ranking
1	1st	1st	1st	1st	1st	1st	1.00	1st
2	2nd	3rd	2nd	2nd	2nd	3rd	2.33	2nd
3	4th	4th	5th	3rd	4th	5th	4.16	4th
4	5th	5th	4th	4th	5th	2nd	4.16	4th
5	3rd	2nd	3rd	5th	3rd	4th	3.33	3rd

Figure 4-49. The overall final rankings for all six possible cases from SCP method

4.8.2 The spatial fuzzy approach in an MCDA context

The spatial fuzzy MCDA methods described in section 4.6 were applied to evaluate various flood damage reduction alternatives. Performances of the alternatives were then compared according to the flowcharts in Figure 4.29. Note that both methods shown in section 4.6 used the same approach to evaluate the alternatives. First, the SFWAM method with two fuzzy membership functions, TMF and SMF, was applied to evaluate the alternatives and then the ISFWAM method was applied. To compare the methods (SFWAM and ISFWAM), the percentage of ranked area in five classes, alternatives 1 ~ 5, were calculated (Figure 4.46). The comparison table and graph of the percentage and overall rankings for each alternative and each weighting set is shown in Table 4.12 and Figure 4.46. The ranking of each alternative was calculated based upon the percentage of grid cells which identified that alternative as the optimal choice, with a higher percentage giving a lower rank number. The percentage of ranked area gave a general idea of which alternative is the most suitable compromise for the entire basin. For example, in this study the weighting set with equal distribution (weight set 6) suggests that about 75.63% of the total area of the Suyoung River Basin is best suited for Alternative 1 (which includes non-flooded area), whereas 8.34%, 1.60%, 13.23%, and 1.24% are best suited for Alternatives 2, 3, 4 and 5 respectively (Figure 4.46). The results of four spatial fuzzy approaches, ISFWAM-TMF, ISFWAM-SMF, SFWAM-TMF and SFWAM-SMF, are also shown in Figure 4.46.

The four spatial fuzzy methods distance metric values and overall rankings in each alternative of weighting set were successfully simulated. However, the simulation results show some subtle differences with respect to the SCP results (Table 4.12). When considering all of weighting sets and alternatives, the final ranking for each alternative was calculated by averaging the related rankings for each weighting set. The average overall ranking for each alternative was then calculated by averaging the final rankings. The average overall rankings were as follows:

Alternative 2 > Alternative 4 > Alternative 5 > Alternative 3.

It shows that Alternative 2 (Levee) is most suitable choice, when all weighting sets are considered. Of course, the final choice always depends on the decision maker. Note that in this analysis Alternative 1 (No Levee) was excluded for two reasons. First, it is not an actual alternative to protect an area from flooding. Second, it is the baseline alternative for explaining the situation of the previous 1991 Gradys flood. Alternative 1 therefore has no meaning when evaluating the alternatives.

Figure 4.46(a) and 4.46(b) compares the two simulation runs with various weighting sets and alternatives. Most of the differences of these two methods are coming from the distance metric values. In the Suyoung area, both methods with the two fuzzy membership functions gave very good performance. While it is hard to measure the performance of the spatial fuzzy approach results, the distance metric values and overall rankings of percentages at each grid cell were used in the spatial fuzzy approach methods. The distance metric values and percentages of rankings throughout basin do not show significant differences between the methods. The distance metric values and percentages, however, show obvious improvements of consideration of imprecision in the analysis as compared to SCP method. The alternatives more diverse and different scores found in the alternatives in the spatial fuzzy approach allowed more discrimination. This is because the consideration of the effect of imprecision on the different locations of the grid cells gave decision makers a greater diversity of answers to compare with what is produced using the deterministic approach.

Major differences are observed between the SFWAM and ISFWAM methods. As can be seen by comparing Figure 4.46(a) and 4.46(b), there is a difference in the percentages within each weighting sets. The most striking difference is that weight set 2 with Alternative 5 had the greatest differences between alternatives, while weight set 4 had the least differences.

In the case of weight set 1 compared with the other methods, ISFWAM-TMF shows different results for Alternative 1 and 2; Alternative 1 has a 10% lower value than those of any other method's average and Alternative 2 is 2.55 times higher (6.78% vs. 17.31%) than those of any others.

However, weight set 2 shows Alternatives 4 and 5 of the ISFWAM-TMF method with different results; Alternative 4 is 9 times higher, and Alternative 5 is 6 times lower than any other method's average.

Weight set 3 shows Alternatives 1 and 4 of the ISFWAM-TMF method with different results; Alternative 1 is 80% lower than any other method's average, and Alternative 4 is 6 times higher (2.42% vs. 14.49%) than the SFWAM method. Alternative 5 is 3.6 times (3.67% vs. 13.17%) higher than that of the SFWAM approach, and approximately 4 times higher than that of ISFWAM-SMF.

Weight sets 4 and 5 show every method has similar results. However, in the case of the SFWAM-TMF method for weight set 5, Alternative 1 is a little lower than that of any other methods, and the SFWAM-SMF method for weight set 5 is a little higher than that of any other methods. This indicates that an increase in any one alternative will cause a proportional decrease for the other alternatives. On the other hand, the ISFWAM-SMF and ISFWAM-TMF methods show similar figures to each other.

In weight set 6, Alternatives 1, 2, and 5 show similar figures. Alternatives 3 and 4, however, show somewhat different results. In this case, Alternative 3 for the SFWAM-SMF method is 9 times higher than that of the other methods, and Alternative 4 value has decreased proportionally.

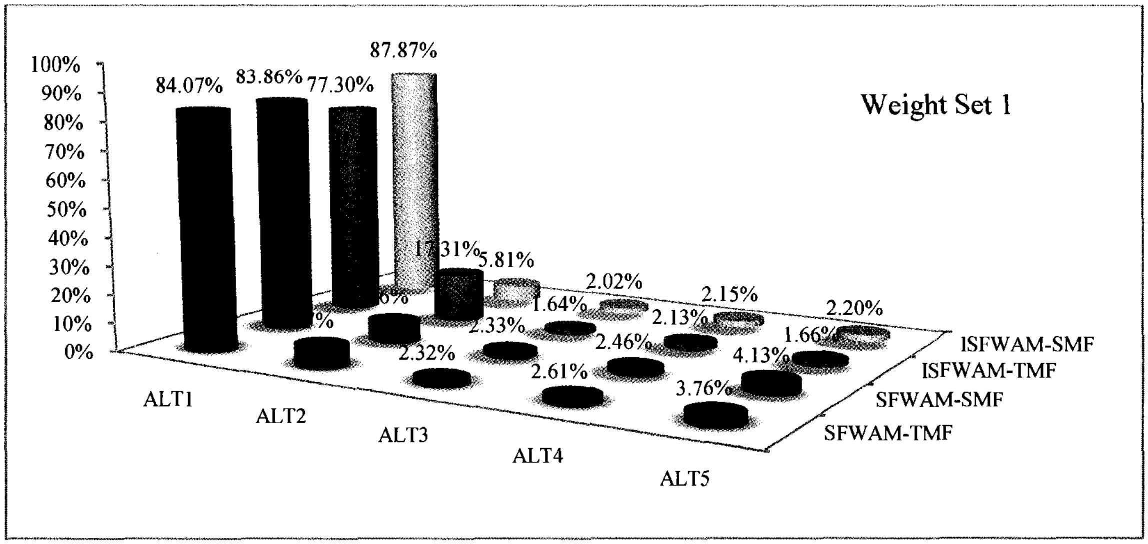
As shown in the above results, one can quickly notice that the range of fluctuation for the SFWAM-SMF and ISFWAM-TMF methods are much higher than that of the SFWAM-TMF and ISFWAM-SMF methods. Moreover, the SFWAM-TMF and ISFWAM-SMF methods both show similar results. It is important to consider the fuzzy membership functions as shown in section 3.4.2, as the S-shaped membership function shows much more diversity of options. It better discriminates among the characteristics of higher ranked alternatives as compared to the triangular membership function.

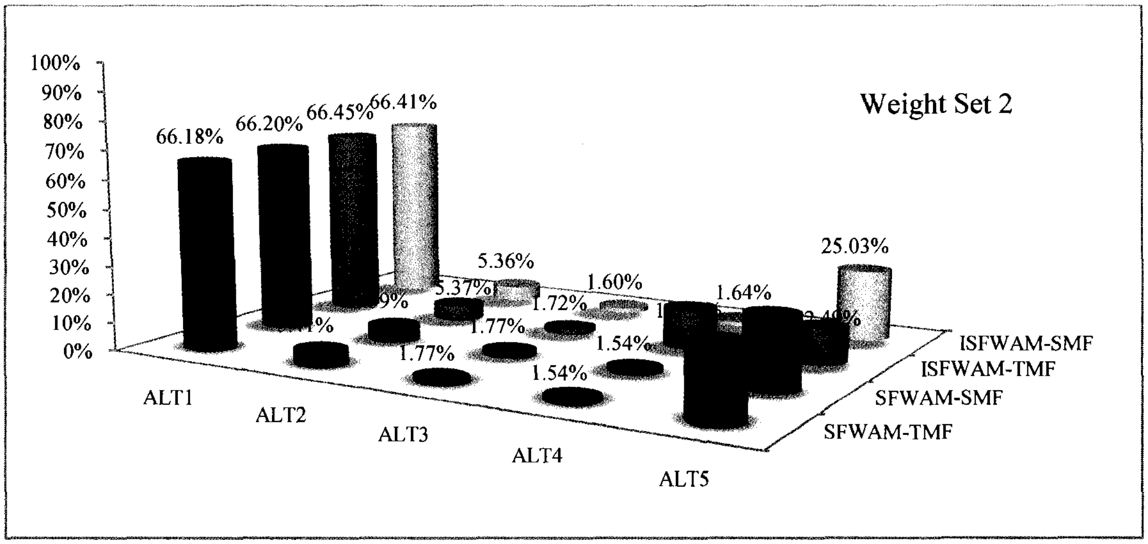
It is therefore not surprising that the ISFWAM-SMF method is better to show greater diversity and greater spatial distribution of the best alternatives and is the final choice for this research. This is also expected because the maximum value of the distance metrics in Figures 4.33 ~ 34 and 4.40 ~ 41 is much lower than that of Figures 4.31 ~ 32 and 4.38 ~ 39. This observation leads to the conclusion that the S-shaped membership function gives more diversity of options than the triangular membership function does. As described by the equations in section 3.3, the larger distance metric value, the higher the degree of membership. Thus, comparing the SFWAM and ISFWAM MCDA methods identified in this study with the ranked alternatives obtained from the developed model, it is found that the ISFWAM -SMF gives more diversity of options. Indeed, Table 4.13 was used to show how well the five alternatives rank relative to each other. This simple table gives some valuable information useful for choosing the most suitable weight set. For example, weight set 6 is ranked first, weight set 1 is ranked second, and weight sets 2, 3, 4, and 5 are fifth, forth, sixth and third respectively. Decision makers can use this table to help pick the most suitable compromise. For instance, it is clear from the table that weight set 6 is the most suitable choice, if Alternatives 3 and 4 are most important to them.

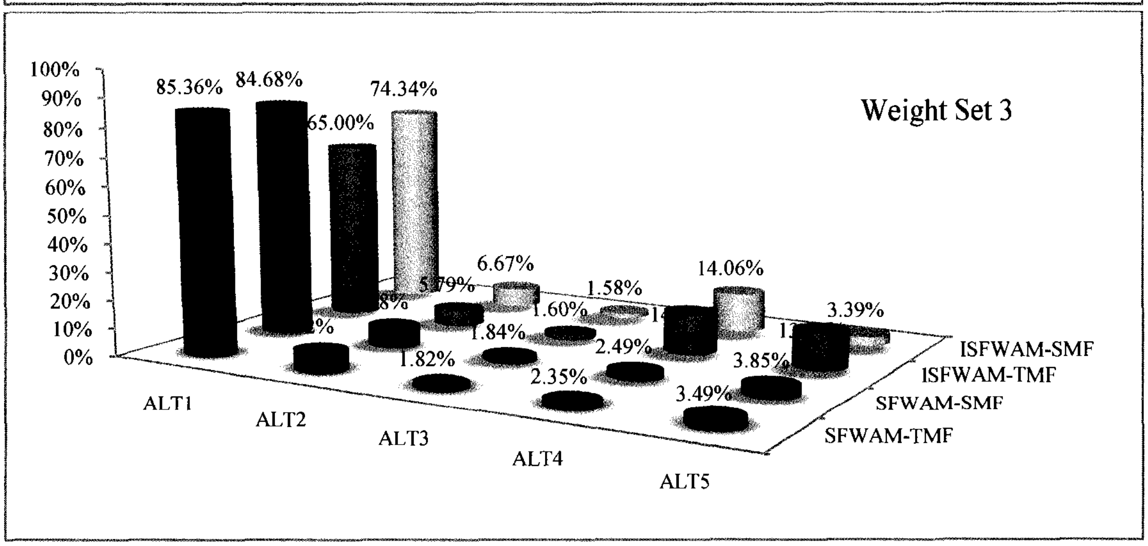
Overall, our comparisons seem to suggest the combination of the ISFWAM method with an S-shaped fuzzy membership function is a more competitive method for giving decision makers greater diversity and definition of the answers. Although calculations of the spatial fuzzy approaches are more demanding than those of the deterministic approaches, the credibility of its results is reason enough for adopting it. This is very important for the making of appropriate decisions based upon the obtained results (Vanegas and Labib 2001). The results shown in this section will help with making the selection of suitable alternatives spatially more diverse. The next step of our research is to compare the deterministic MCDA (SCP) and spatial fuzzy MCDA (ISFWAM-SMF) methods.

Table 4-12. Overall rankings from the spatial fuzzy approaches for each alternative

Weight Set	Method	Alternative 2	Alternative 3	Alternative 4	Alternative 5
	SFWAM-TMF	1^{st}	4^{th}	3^{rd}	2^{nd}
	SFWAM-SMF	1^{st}	4^{th}	3^{rd}	2^{nd}
1	ISFWAM-TMF	1^{st}	4^{th}	2^{nd}	3^{rd}
	ISFWAM-SMF	1^{st}	4^{th}	3^{rd}	2^{nd}
	Final ranking	[redacted]	4^{th}	3^{rd}	2^{nd}
	SFWAM-TMF	2^{nd}	3^{rd}	4^{th}	1^{st}
	SFWAM-SMF	2^{nd}	3^{rd}	4^{th}	1^{st}
2	ISFWAM-TMF	3^{rd}	4^{th}	1^{st}	2^{nd}
	ISFWAM-SMF	2^{nd}	4^{th}	3^{rd}	1^{st}
	Final ranking	2^{nd}	4^{th}	3^{rd}	[redacted]
	SFWAM-TMF	1^{st}	4^{th}	3^{rd}	2^{nd}
	SFWAM-SMF	1^{st}	4^{th}	3^{rd}	2^{nd}
3	ISFWAM-TMF	3^{rd}	4^{th}	1^{st}	2^{nd}
	ISFWAM-SMF	2^{nd}	4^{th}	1^{st}	3^{rd}
	Final ranking	2^{nd}	4^{th}	[redacted]	3^{rd}
	SFWAM-TMF	1^{st}	2^{nd}	3^{rd}	4^{th}
	SFWAM-SMF	1^{st}	2^{nd}	3^{rd}	4^{th}
4	ISFWAM-TMF	1^{st}	2^{nd}	3^{rd}	4^{th}
	ISFWAM-SMF	1^{st}	2^{nd}	3^{rd}	4^{th}
	Final ranking	[redacted]	2^{nd}	3^{rd}	4^{th}
	SFWAM-TMF	1^{st}	2^{nd}	4^{th}	3^{rd}
	SFWAM-SMF	1^{st}	2^{nd}	4^{th}	3^{rd}
5	ISFWAM-TMF	1^{st}	3^{rd}	2^{nd}	4^{th}
	ISFWAM-SMF	1^{st}	2^{nd}	3^{rd}	4^{th}
	Final ranking	[redacted]	2^{nd}	4^{th}	3^{rd}
	SFWAM-TMF	2^{nd}	3^{rd}	1^{st}	4^{th}
	SFWAM-SMF	2^{nd}	1^{st}	3^{rd}	4^{th}
6	ISFWAM-TMF	2^{nd}	3^{rd}	1^{st}	4^{th}
	ISFWAM-SMF	2^{nd}	3^{rd}	1^{st}	4^{th}
	Final ranking	2^{nd}	3^{rd}	[redacted]	4^{th}
Average overall ranking		[redacted]	3.0 (4^{th})	2.6 (2^{nd})	2.9 (3^{rd})


Weight Set 1
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
84.07%
83.86%
77.30%
87.87%
5.81%
2.02%
1.64%
2.33%
2.13%
2.15%
2.20%
1.66%
2.32%
2.46%
2.61%
4.13%
3.76%
ALT1
ALT2
ALT3
ALT4
ALT5
ISFWAM-SMF
ISFWAM-TMF
SFWAM-SMF
SFWAM-TMF


Weight Set 2
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
66.18%
66.20%
66.45%
66.41%
5.36%
5.37%
1.60%
1.72%
1.77%
1.64%
25.03%
1.77%
1.54%
1.54%
ALT1
ALT2
ALT3
ALT4
ALT5
ISFWAM-SMF
ISFWAM-TMF
SFWAM-SMF
SFWAM-TMF


Weight Set 3
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
85.36%
84.68%
65.00%
74.34%
6.67%
1.58%
1.60%
1.84%
14.06%
3.39%
1.82%
2.49%
3.85%
2.35%
3.49%
ALT1
ALT2
ALT3
ALT4
ALT5
ISFWAM-SMF
ISFWAM-TMF
SFWAM-SMF
SFWAM-TMF

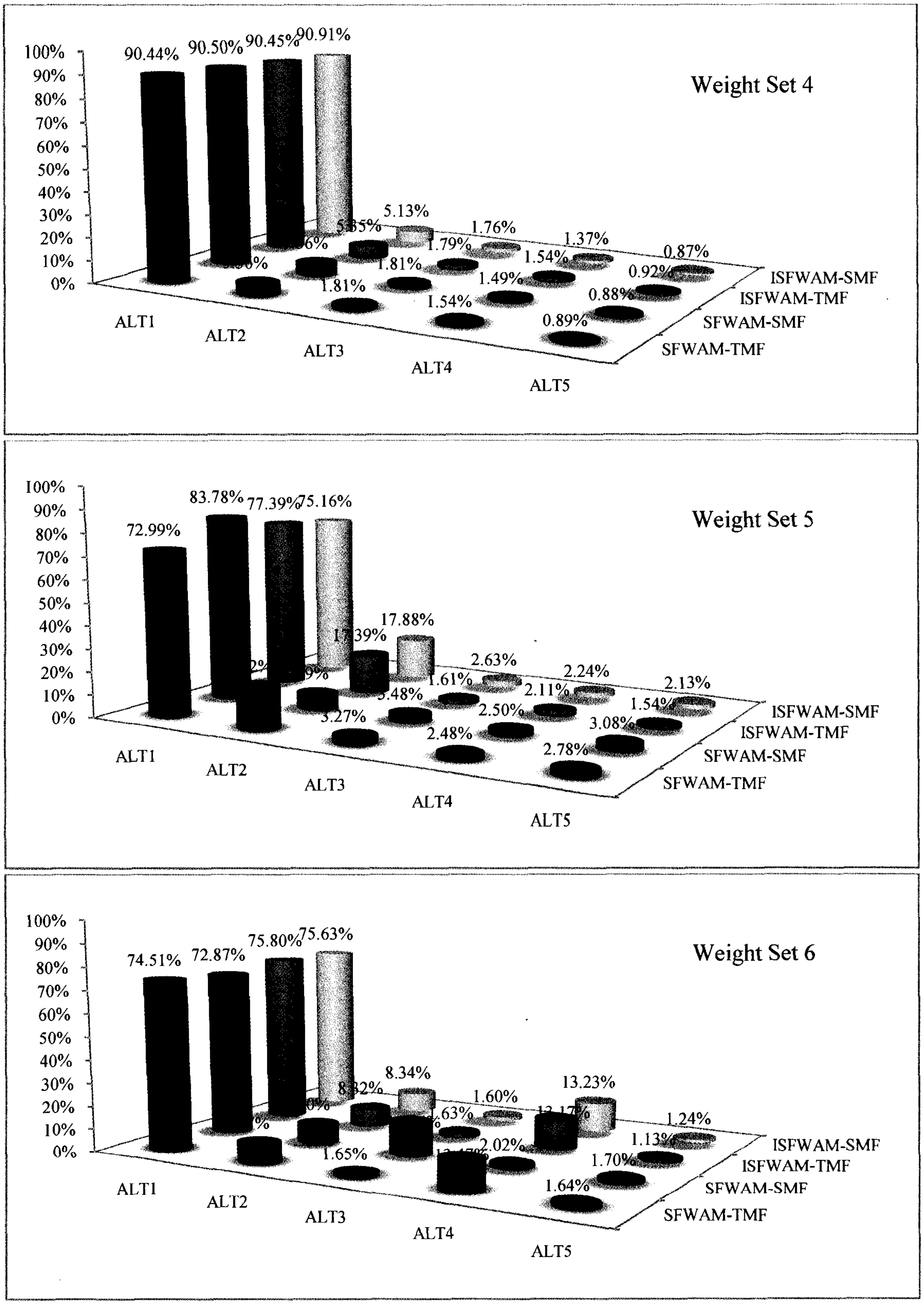


Figure 4-50. The percentage of ranked area in five classes

Table 4-13. Overall rankings from the spatial fuzzy approaches for each weighting set

Alternative	Ranking of each weighting set					
	Weight Set 1	Weight Set 2	Weight Set 3	Weight Set 4	Weight Set 5	Weight Set 6
1	2nd	6th	4th		5th	3rd
2	2nd	5th	4th	6th		3rd
3	3rd	5th	6th	4th	2nd	
4	4th	3rd	2nd	6th	5th	
5	3rd		2nd	6th	4th	5th
Average overall ranking	2.8 (**2nd**)	4 (**5th**)	3.6 (**4th**)	4.6 (**6th**)	3.4 (**3rd**)	

4.8.3 Comparison of deterministic MCDA and spatial fuzzy MCDA

The purpose of this section is to provide a comprehensive assessment of the advantages and limitations of different MCDA techniques that are used to evaluate flood damage reduction alternatives. This comparison was conducted on both deterministic and spatial fuzzy MCDA methods (SCP and ISFWAM-SMF) using a GIS-based MCDA interactive model.

In this section, only the SCP method was chosen for representing the deterministic MCDA technique due to the lack of considering the unique characteristics at all points in the CP method (section 4.7) as compared to the SCP method. As the ISFWAM-SMF method was shown in section 4.7.3 to have a greater diversity and better definition of the answers of all the spatial fuzzy MCDA methods, it will be used to represent the spatial fuzzy approach.

In Figure 4.47, we found the results obtained by the developed system. This figure is the average overall rankings of the SCP and SFWAM-SMF methods for each alternative as given by a GIS-based MCDA interactive model. More insight into the differences between the deterministic and spatial fuzzy approaches is shown in the ranking results of Table 4.14. The percentage of average ranking in each alternative gives a general idea of which alternative has better definition and suitable compromise for the entire basin. The table and figure show relatively large differences between the two methods are found in the results for Alternatives 3, 4, and 5. Along with the visual representations of Figure 4.47, the table shows the percentage of ranked alternative for each weight set.

Note that we can find detailed information about the overall ratio of the SCP and

ISFWAM-SMF methods for the combined weight sets from the percent column in the table. For several cases, the ratio of percentages of the ranked alternatives of the two methods is greatly increased or decreased (90.79% ~ 139.72%). Generally, larger differences are observed for Alternatives 3 ~ 5. It is quite interesting that the ranking of each alternative starts changing (shown in Figure 4.47), if the ratio of percentages of ranked alternatives of the SCP and ISFWAM-SMF methods is greater than approximately 110% or less than 90%. The percentage ratio of the SCP method is higher than the ISFWAM-SMF method in Alternatives 3 and 5. This corresponds to an increase to the next higher rank, as shown in Figure 4.47. For Alternative 4, it corresponds to a decrease to the next lower rank. When the MCDA method is changes, Alternatives 3 ~ 5 are more likely to change rankings. However, Alternatives 1 and 2 are not sensitive at all. Note we could disregard Alternative 1 in this analysis because of its characteristics as described in section 4.7.2.

The ISFWAM-SMF method was able to divide the alternatives with greater precision that the SCP method. The ISFWAM-SMF method provided the ability to have even more definition and discrimination in terms of the alternatives that might be best for entire area. For example, the preference order for alternative ranking in the SCP method was:

Alternative 1 > Alternative 2 > Alternative 5 > Alternative 3 = Alternative 4.

In this case, both Alternatives 3 and 4 are equally ranked. However, the ISFWAM-SMF method produced the following ranking:

Alternative 1 >Alternative 2 > Alternative 4 > Alternative 5 > Alternative 3.

Here Alternatives 3 and 4 are clearly separated. This gives the decision maker clearer and more detailed information, for when the decision maker finds the choice of alternative ambiguous. The ranks of the ISFWAM-SMF method enlarge the range of one's choice and clearance. As we can see in Figure 4.47, it is not obvious which of Alternatives 3 ~ 5 is the clear choice if the results of the SCP method are the data upon which to decide. Figures 4.28 and 4.43 illustrate the spatially ranked maps of the SCP and ISFWAM-SMF methods respectively. The maps show the advantage of the spatial fuzzy approach (ISFWAM-SMF) as it provides the ability to have more detail about the gradual transition of the suitability of the each alternative and more definition and discrimination in terms of the alternatives that might be best for particular spatial locations. The range of the ranking value has a lot of detail and fluctuation in this figure. Moreover, this figure shows that it is possible to describe in more detail the Geum-Sa area, which is located in the upper stream of the Suyoung River, meaning that it is easy to choose one of the most suitable alternatives or to plan flood-control measures in an area of interest. These simple ranking maps give decision makers the capability to discriminate between the higher ranked and lower ranked alternatives.

Our research reveals that the spatial fuzzy approach implemented in this paper is better not only because it produces less ambiguity, but also because it provides more detail about the gradual transition of the suitability of each alternative. For the case study in the Suyoung River Basin, the answers more diverse and showed more differences in the scores of the alternatives which allowed additional discrimination. Thus, the concept of fuzzy theory is a powerful tool for evaluating the discriminating alternatives with a deterministic MCDA method, since using fuzzy theory improves the consideration of the imprecision in the analysis.

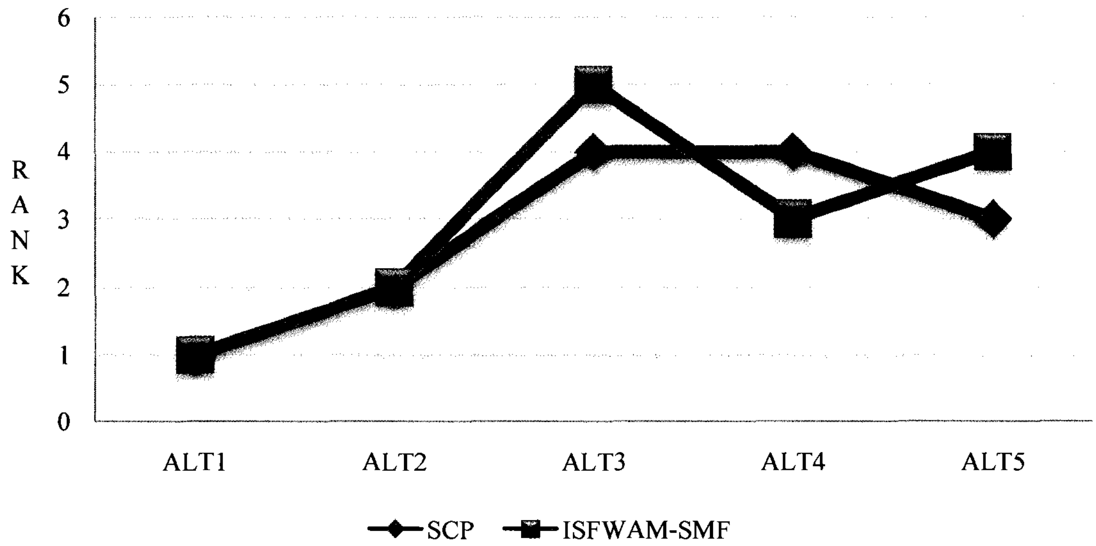


Figure 4-51. Average overall rankings of the SCP and SFWAM-SMF methods for each alternative

Table 4-14. The percentage of locations where an alternative is preferred based upon different weight sets and methods

Alt	Methodology	Perspective of each alternative (%)						Ratio of percentage (SCP/ISFWAM)
		W.S #1	W.S #2	W.S #3	W.S #4	W.S #5	W.S #6	
1	SCP	83.49	66.06	84.29	90.40	72.21	73.66	100.17% (·)
	ISFWAM-SMF	87.83	66.38	74.31	90.87	75.13	75.59	
2	SCP	7.39	5.44	7.24	5.35	19.06	9.06	109.50% (·)
	ISFWAM-SMF	5.81	5.36	6.66	5.12	17.88	8.34	
3	SCP	2.36	1.73	2.01	1.82	2.79	1.71	111.38% (↑)
	ISFWAM-SMF	2.02	1.60	1.58	1.76	2.63	1.60	
4	SCP	2.34	1.55	2.45	1.53	2.45	13.53	90.79% (↓)
	ISFWAM-SMF	2.15	1.64	14.05	1.37	2.24	13.22	
5	SCP	4.42	25.20	4.01	0.90	3.49	1.88	139.72% (↑)
	ISFWAM-SMF	2.20	25.02	3.39	0.87	2.13	1.24	

4.8.4 Comparison of adjusted and unadjusted DEM maps using a spatial fuzzy MCDA approach

Figure 4.48 presents the subtraction map between the adjusted DEM and the unadjusted DEM, and Figure 4.49 compares the calculated percentages of ranked area for five alternatives. The ISFWAM-SMF technique was applied for this comparison.

Since the adjusted DEM shows better performance estimating flood inundation area relative to the unadjusted DEM in section 4.3, the adjusted DEM was used as the base map for the MCDA. Because the subtraction map is based upon each of the DEM maps, some important characteristics are revealed from the values in this figure. There is quite a change in the grid values inside the floodplain boundary and there is a great change of values within the 100-yr floodplain. However, unlike inside of the floodplain boundary, there is a little value change outside the floodplain boundary. This occurs because the change (difference) value was incorporated for this floodplain analysis. In any case, the MCDA should be calculated with various criteria. Therefore, it can be concluded that there are big changes inside of the floodplain when it is calculated with any other criteria. It shows clearly that the adjusted DEM gives better floodplain simulation results, as shown in section 4.3.2. It is also obvious that the difference of the performances between the adjusted DEM and the unadjusted DEM are greater inside the Suyoung area. It is therefore not surprising that use of an unadjusted DEM in the Suyoung River Basin might not give sufficient information for determining flood inundation.

The comparison graph and table of the percentage and ranking for each alternative and weighting set is shown in Figure 4.49. With the unadjusted DEM, Alternative 2 is sometimes chosen erroneously. This mostly happens inside of the floodplain. Extensive comparisons for a variety of cases also bear out this conclusion (section 4.3.2).

Overall, the above results illustrate the adjusted DEM, namely, that this modification of DEM as described in section 4.3.1 provides more detail about not only the stream channel but also the general landscape. It also demonstrates why the unadjusted DEM should not be used and especially if the quality of the DEM is poor as it was in this case.

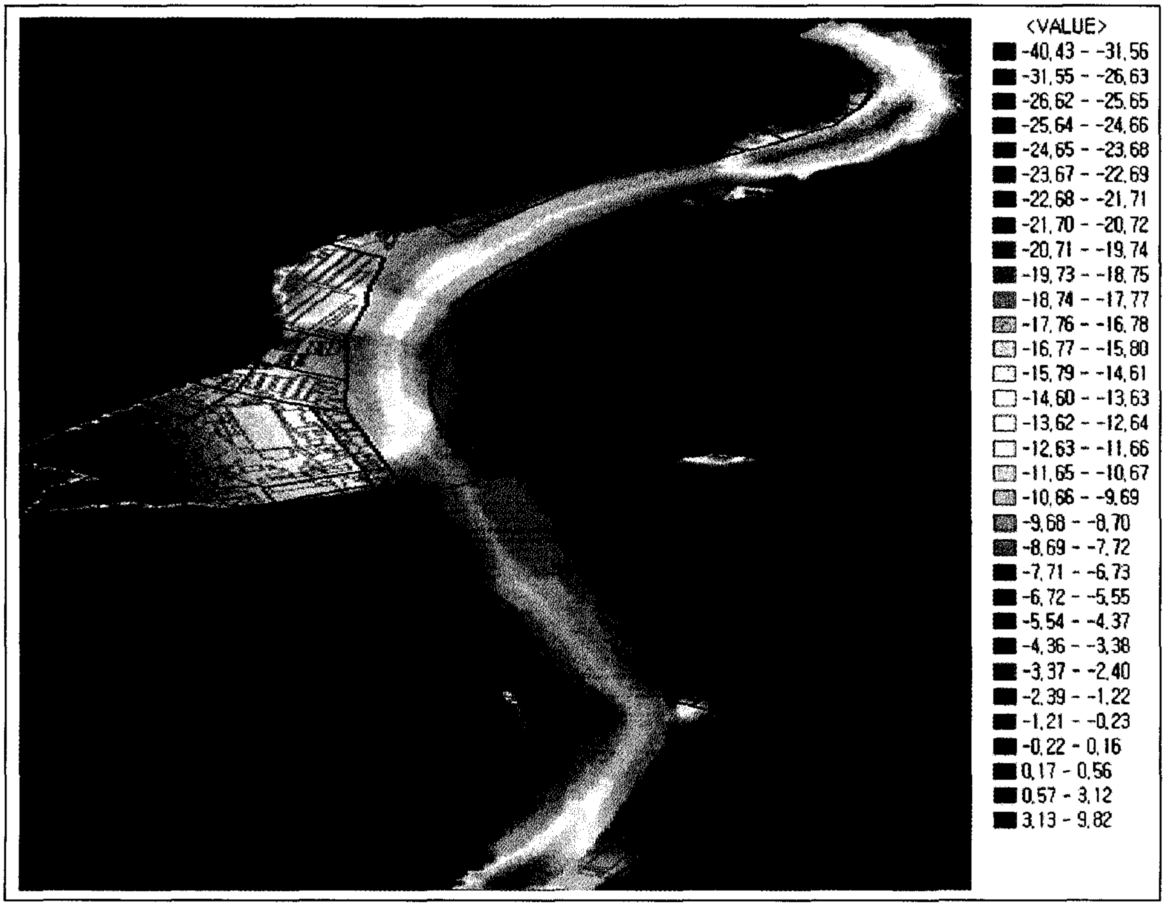
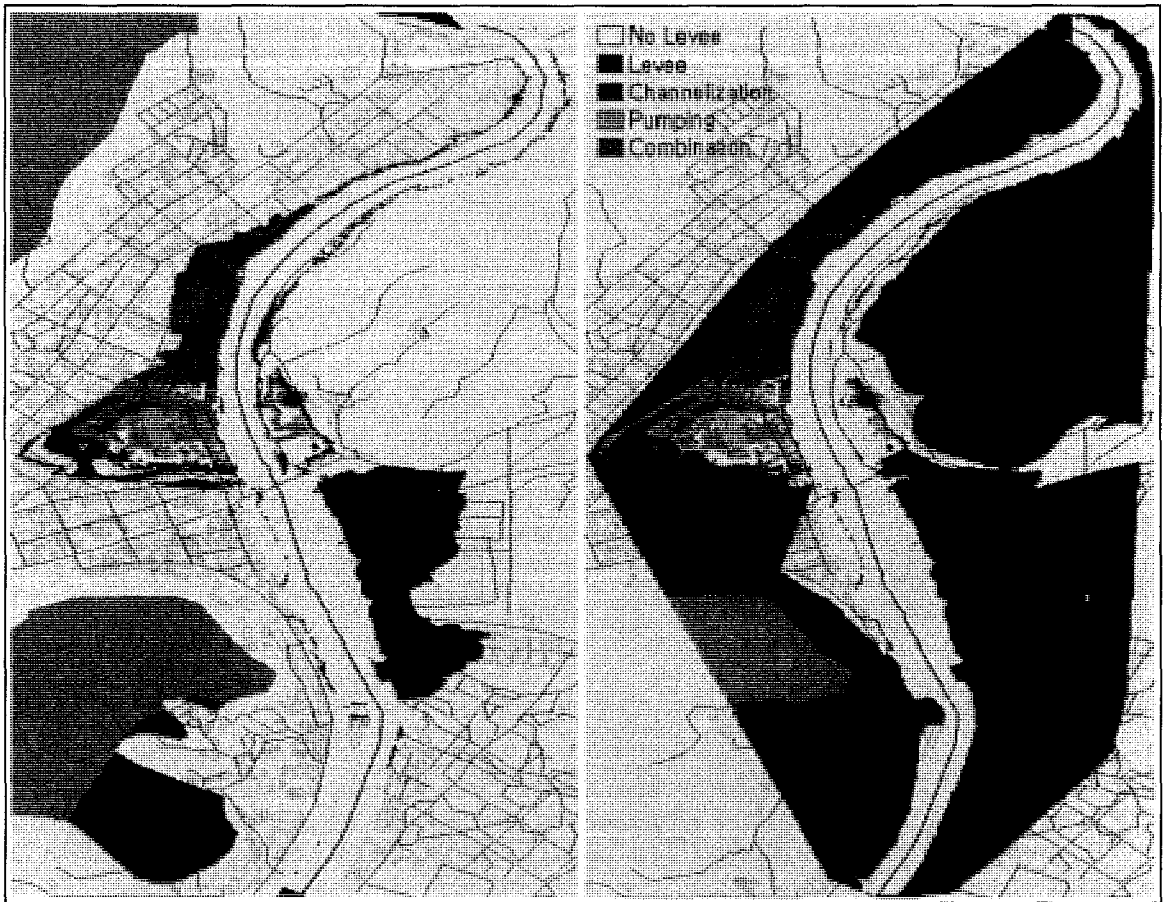


Figure 4-52. Subtraction of unadjusted DEM from adjusted DEM for alternative1 (ISFWAM-SMF, 5m and weight set 6)



Base Map	Alternative1	Alternative2	Alternative3	Alternative4	Alternative5
Unadjusted DEM	50.28% (1st)	43.20% (2nd)	1.51% (4th)	4.02% (3rd)	0.98% (5th)
Adjusted DEM	75.59% (1st)	8.34% (3rd)	1.60% (4th)	13.22% (2nd)	1.24% (5th)

Figure 4-53. Comparison of percentages and rankings of alternatives based upon the adjusted and unadjusted DEM (ISFWAM-SMF, 5*m* and weight set 6)

4.8.5 Impact of inserting additional criteria into the MCDA

The results from the previous section show that DEM accuracy is a very sensitive factor for the different MCDA methods. In this study, the adjusted DEM was used as a base map for the MCDA while evaluating suitable alternatives.

The remaining question for this research becomes the impact of the number of criteria on the alternatives selected. Again the goal is to develop information to determine if there exists diversity in the best options for different spatial locations. If there is only one criterion, then the alternative that has the highest rating for that criterion will be ranked the best. This could mask important variations in the answer. If there are multiple criteria, it is not possible to know in advance whether a small number or large number of alternatives will emerge as the best. In other words, the possible impact of inserting additional criteria into the MCDA could cause more or less diversity of preferred options. This portion of the research was conducted to determine how individual criteria and the number of criteria impact the diversity or discrimination of options.

Data was available for a total of 31 criteria combination sets, of which five criteria and five alternatives were used for this section. Analysis was performed to evaluate the impact of inserting 1 to 5 additional criteria for all floodplain alternatives. For better comparison, the results of MCDA techniques have been calculated with ISFWAM-SMF, 100-yr flood, 5-*m* resolution DEM, and an equally weighted weighting set. The ISFWAM-SMF was implemented in the same way as described in section 4.6, and the resulting ranking map is shown in Figure 4.52.

A significant amount of time is required to calculate 31 criteria combination sets. The fully automated calculation module in the developed MCDA model (Figure 4.50) was implemented for the benefit of the end-user. In addition, this module reduces calculation time and cumbersome work. It requires only one click to perform the whole set of criteria combinations, producing distance metric files for each criteria combination set, as shown on the right side of Figure 4.50. Standardization and ranking procedures were performed using the IDRISI GIS program.

Before evaluating the impact of inserting additional criteria, the work in this section tried to determine the impact of individual criteria. In case of Alternative 1, Figure 4.51 shows the percentage of the locations where this alternative is the preferred option. Note that the impact of individual criteria or combinations of criteria can lead to sharp fluctuations in this alternative's percentage. Further, it was found that criteria 1, 2 and 3 had more impact than criteria 4 and 5. However, in the case of Alternative 2, criterion 5 significantly influences the results. The influential criteria vary with the alternatives considered. While this is expected from the perspective of the technical specialist, this fact may not be apparent to the final decision makers. For Alternative 3, criterion has a significant impact. For Alternative 4, the combination of criteria 3 through criteria 5 is significant, and for Alternative 5, criteria 2 and 3 are significant. It is important to note that by identifying the criteria that are significant for every alternative increase the possibility to discriminate between candidate strategies.

More insights into the impact of additional criteria are shown in Figure 4.52. Five ranked maps, adding 1 to 5 criteria, are generated by the MCDA model for the area of interest. This shows that adding criteria produces more detail on the use of various alternatives in the MCDA results. It is also obvious that the diversity of the answers between using fewer criteria and more criteria is larger in the Suyoung area. The additional criteria clearly make the selection of alternative spatially more diverse. Applying a one-criterion result is simple. However, the more criteria that are added, the more clearly it is shown which alternative is most appropriate for any particular location. One can infer that by adding criteria it is possible to show greater diversity and greater spatial distribution of the best alternatives. Table 4.15 shows the detailed percentages for each alternative and criteria combination.

Overall, the criteria are one of the important considerations in the evaluation of alternatives. It is therefore not surprising that an MCDA with additional criteria produces more diversity of options than with fewer criteria.

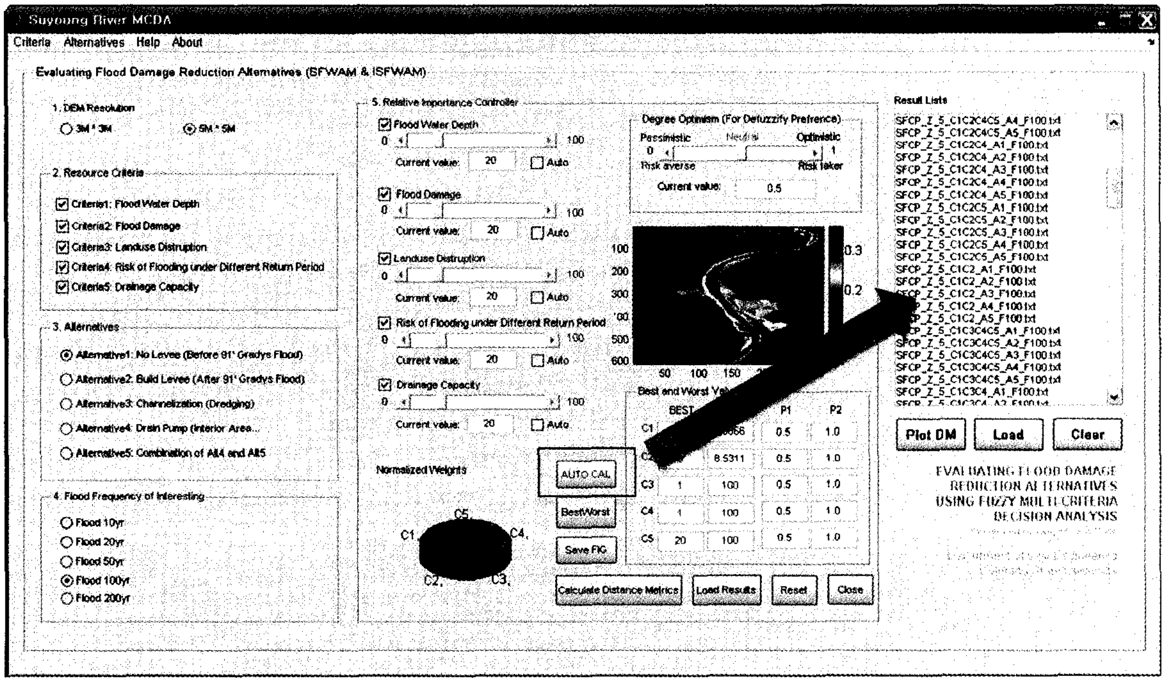


Figure 4-54. Auto calculation option

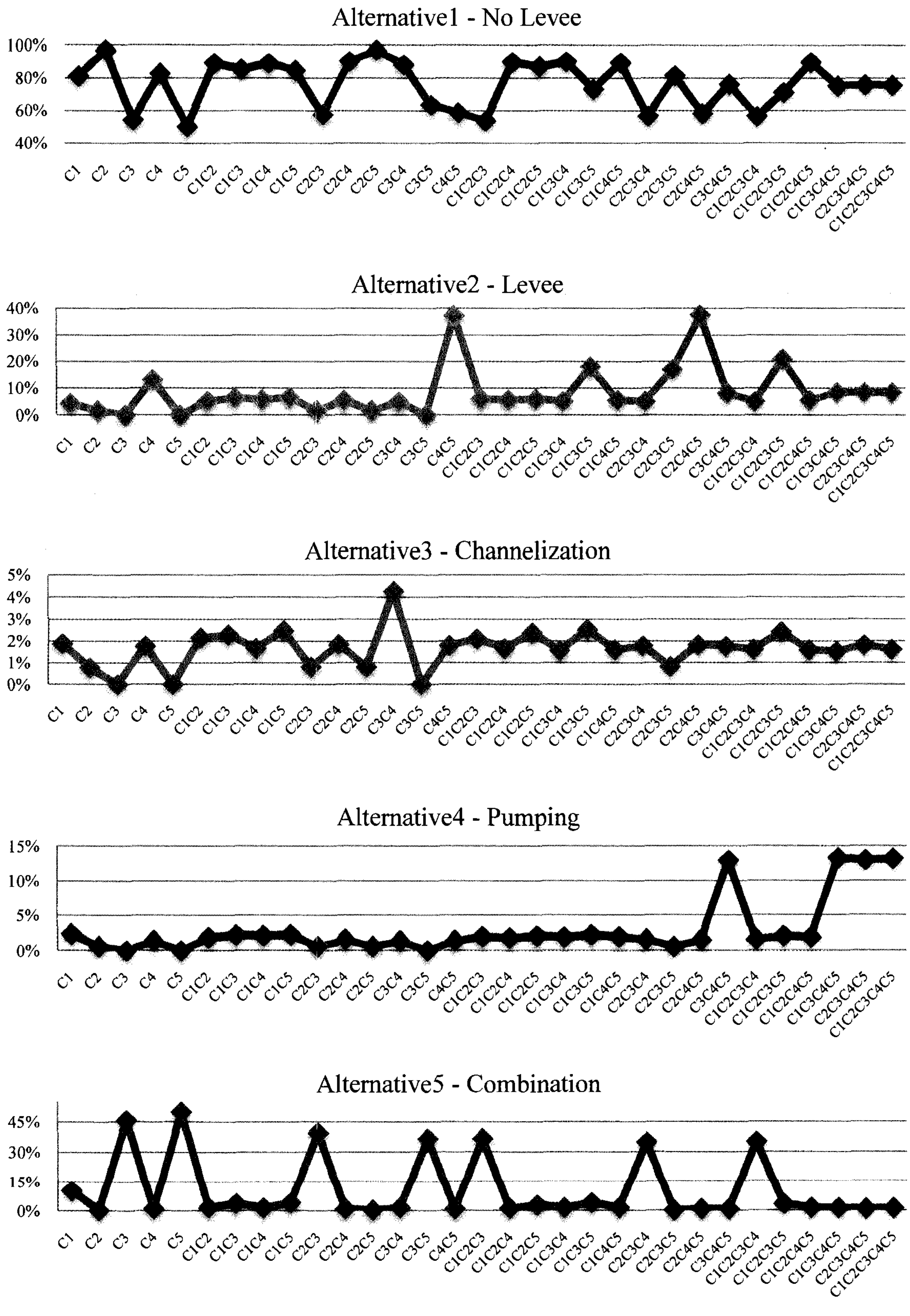


Figure 4-55. The percentage of the locations where that alternative is preferred

Table 4-15. The percentage of spatial locations where each alternative is the preferred based upon the different criteria combination sets

Combination	Alternative1	Alternative2	Alternative3	Alternative4	Alternative5
C1	140,843 (81.3%)	7,413 (4.3%)	3,257 (1.9%)	4,075 (2.4%)	17,692 (10.2%)
C2	167,946 (96.9%)	2,725 (1.6%)	1,340 (0.8%)	1,019 (0.6%)	250 (0.1%)
C3	94,226 (54.4%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	79,054 (45.6%)
C4	143,499 (82.8%)	22,874 (13.2%)	3,050 (1.8%)	2,351 (1.4%)	1,506 (0.9%)
C5	86,978 (50.2%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	86,302 (49.8%)
C1C2	154,793 (89.3%)	8,899 (5.1%)	3,738 (2.2%)	3,165 (1.8%)	2,685 (1.5%)
C1C3	147,920 (85.4%)	11,105 (6.4%)	3,973 (2.3%)	3,866 (2.2%)	6,416 (3.7%)
C1C4	154,600 (89.2%)	9,951 (5.7%)	2,884 (1.7%)	3,625 (2.1%)	2,220 (1.3%)
C1C5	146,795 (84.7%)	11,427 (6.6%)	4,295 (2.5%)	3,907 (2.3%)	6,856 (4.0%)
C2C3	99,906 (57.7%)	2,721 (1.6%)	1,398 (0.8%)	1,021 (0.6%)	68,234 (39.4%)
C2C4	156,397 (90.3%)	9,459 (5.5%)	3,195 (1.8%)	2,652 (1.5%)	1,577 (0.9%)
C2C5	167,744 (96.8%)	2,815 (1.6%)	1,391 (0.8%)	1,042 (0.6%)	288 (0.2%)
C3C4	152,746 (88.1%)	8,308 (4.8%)	7,375 (4.3%)	2,333 (1.3%)	2,518 (1.5%)
C3C5	110,238 (63.6%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	63,042 (36.4%)
C4C5	101,922 (58.8%)	64,397 (37.2%)	3,102 (1.8%)	2,353 (1.4%)	1,506 (0.9%)
C1C2C3	93,000 (53.7%)	10,213 (5.9%)	3,640 (2.1%)	3,342 (1.9%)	63,085 (36.4%)
C1C2C4	155,729 (89.9%)	9,710 (5.6%)	2,878 (1.7%)	3,011 (1.7%)	1,952 (1.1%)
C1C2C5	150,658 (86.9%)	10,186 (5.9%)	4,121 (2.4%)	3,523 (2.0%)	4,792 (2.8%)
C1C3C4	156,044 (90.1%)	8,821 (5.1%)	2,695 (1.6%)	3,224 (1.9%)	2,496 (1.4%)
C1C3C5	127,048 (73.3%)	31,178 (18.0%)	4,368 (2.5%)	3,832 (2.2%)	6,854 (4.0%)
C1C4C5	154,950 (89.4%)	9,572 (5.5%)	2,764 (1.6%)	3,359 (1.9%)	2,635 (1.5%)
C2C3C4	98,377 (56.8%)	8,782 (5.1%)	3,085 (1.8%)	2,674 (1.5%)	60,362 (34.8%)
C2C3C5	141,133 (81.4%)	29,425 (17.0%)	1,407 (0.8%)	1,026 (0.6%)	289 (0.2%)
C2C4C5	100,975 (58.3%)	64,924 (37.5%)	3,151 (1.8%)	2,654 (1.5%)	1,576 (0.9%)
C3C4C5	132,148 (76.3%)	14,131 (8.2%)	3,047 (1.8%)	22,448 (13.0%)	1,506 (0.9%)
C1C2C3C4	98,159 (56.6%)	8,760 (5.1%)	2,792 (1.6%)	2,809 (1.6%)	60,760 (35.1%)
C1C2C3C5	123,437 (71.2%)	36,238 (20.9%)	4,196 (2.4%)	3,603 (2.1%)	5,806 (3.4%)
C1C2C4C5	155,140 (89.5%)	9,571 (5.5%)	2,746 (1.6%)	3,285 (1.9%)	2,538 (1.5%)
C1C3C4C5	130,478 (75.3%)	14,661 (8.5%)	2,641 (1.5%)	23,084 (13.3%)	2,416 (1.4%)
C2C3C4C5	131,390 (75.8%)	14,600 (8.4%)	3,141 (1.8%)	22,580 (13.0%)	1,569 (0.9%)
C1C2C3C4C5	130,991 (75.6%)	14,453 (8.3%)	2,774 (1.6%)	22,912 (13.2%)	2,150 (1.2%)

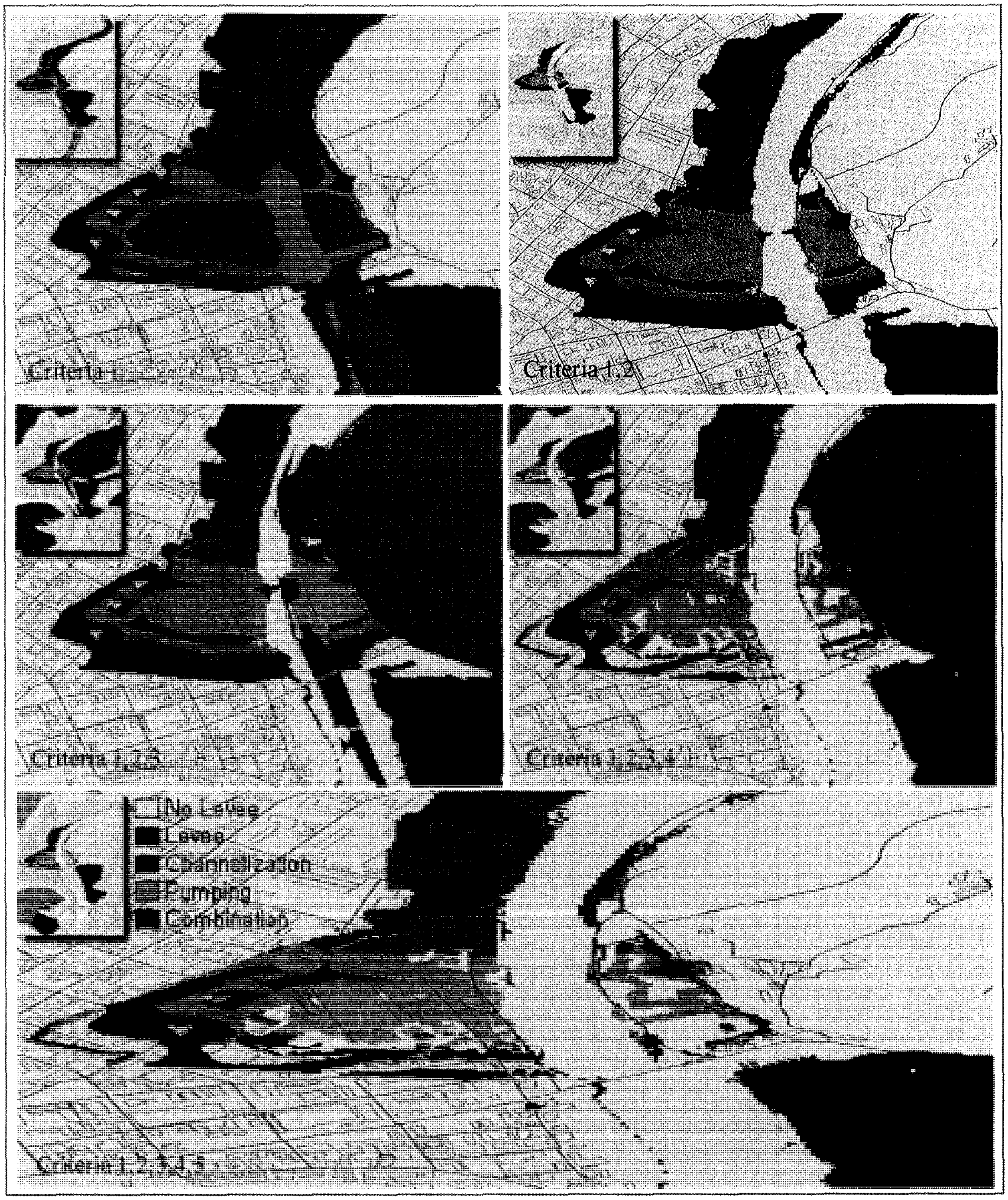


Figure 4-56. Detailed ranking map showing the changes in the distribution of the preferred alternatives as impacted by additional criteria for the Geumsa area

CHAPTER 5: SUMMARY AND RECOMMENDATIONS

5.1 Summary

The research described in this dissertation meets the objective of the development of a methodology for improving consideration of imprecision using GIS and spatial fuzzy MCDA. The methodology was developed and applied as a GIS-based MCDA interactive model designed to give end-users a convenient tool for floodplain management. The developed model was programmed in Matlab software.

The target region for a demonstration application of the methodology was the Suyoung River Basin in Korea. The 1991 Gladys flood event and five different return periods were used as a case study to demonstrate the proposed methodology of evaluation of various flood protection alternatives.

The results of this work have been carefully driven by combining the available low accuracy DEM with existing surveyed channel elevation data (HEC-RAS). Based upon this improved DEM, different MCDA techniques were applied and compared to the area of interest. Finally, the impacts of inserting additional criteria into the MCDA were determined. Of all the MCDA approaches tested, the best results were obtained with the ISFWAM-SMF method. This research was divided into four main parts; (1) the use of GIS to manipulate Digital Elevation Models (DEM), (2) a GIS-based MCDA interactive model, (3) the deterministic approach of MCDA, and (4) the spatial fuzzy approach of

MCDA.

5.1.1 The Use of GIS to Manipulate Digital Elevation Models

Stream channel representation data quality is compared for an adjusted DEM and an unadjusted DEM in section 4.3. Then a comparison between the actual 1991 Gradys flood event map and a simulated flood inundation map using the adjusted DEM for the simulation of flooding was conducted. The adjusted DEM performed quite well in estimating the flood inundation area for five different return period floods. The results of the analysis were as follows:

- The problems posed by the low resolution available were solved by combining HEC-RAS channel data with the lower accuracy stream channel DEM. The combined map more faithfully depicts the floodplain area than the original DEM since the combined map contains additional data on the shape of the stream channel.
- GIS provides a proper framework for the application of spatial analysis methods of MCDA, which does not have its own data management facilities for the capture, storage, retrieval, editing, transformation, and display of spatial data (Carver 1991).

5.1.2 A GIS-based MCDA interactive model

In order to evaluate flood damage reduction alternatives in the Suyoung River Basin, an MCDA interactive model containing all of the decision parameters was developed. The overall conclusions drawn by section 4.4 can be briefly summarized as follows:

- A GIS-based MCDA interactive model has been designed to integrate available computer technologies with modeling and analysis tools in a user-friendly environment to provide maximum flexibility.

- The developed model provides not only a powerful tool for the user to make decisions but also has an easy to use GUI that abstracts the end-user from the concepts of fuzzy MCDA theory. The only required user input is the selection of clearly explained menu items.
- The developed model provides decision makers the ability to compute the best flood management alternative for each spatial location in the basin and to display this diversity of preferred options. Since a single alternative will likely be selected for the entire basin, decision makers can evaluate each alternative using the developed "cost of uniformity" metric. This has the potential to provide a more rational, objective, and transparent approach to making decisions.

5.1.3 The deterministic approach in an MCDA context

Based upon the two selected deterministic MCDA approaches suggested in section 4.5, differences in simulation results were evaluated and ranked non-spatially (CP) or spatially (SCP) in the region of interest for evaluation of flood damage reduction alternatives. For better comparison of the differences of simulated ranking maps, six weight sets were used individually for each result. Some of the findings from this work include:

- The CP method computed a single value per region for each of the alternatives. On the other hand, with the SCP method a distance metric per alternative was calculated for each impacted location within the region, which gives decision makers the capability with spatial analysis not to just use a single strategy for an entire geographical region but to determine if different strategies might have an advantage for the different spatial characteristics at different points in the floodplain. Overall, the SCP method gave decision maker the possibility to find more spatially distributed strategies.

- Differences in ranking of alternatives in both methods (CP and SCP) are clearly shown in the result. The performance of SCP provides the ability to have even more definition and discrimination in terms of the alternatives that might be best for particular spatial locations.

5.1.4 The spatial fuzzy approach in an MCDA context

As shown in section 4.6, the spatial fuzzy approach suggested in the work of Chapter 3 is an MCDA technique designed to consider the effect in the rating scale, the preferences of decision maker, and various parameters that those numbers have imprecision, vagueness, or uncertainty. The differences between SFWAM and ISFWAM were presented in section 4.7.2, along with the differences in two fuzzy membership functions (TMF and SMF), and the impact of inserting additional criteria on the results was analyzed by comparing each ranking map (section 4.7.5). Each MCDA technique was performed based upon a GIS-based MCDA interactive model. The results found in this chapter are as follows:

- The final ranking images of representative deterministic and spatial fuzzy approaches show slight differences while overall distance metric values of each alternative are very different. This is because the different MCDA methods lead to a different values of the distance metric at each grid cell.

- The two spatial fuzzy approaches (SFWAM and ISFWAM) overall rankings are different in many aspects. Defuzzified distance metric values from the SFWAM method were larger than those of the ISFWAM method, and overall the comparisons suggest that the ISFWAM using SMF gives a greater diversity of the preferred alternatives.
- The resulting defuzzified distance metric from the spatial fuzzy approach, which represents the overall desirable surroundings of evaluated candidate alternatives, is more diverse and more discriminative than the distance metric value obtained through the conventional deterministic approach, which may produce rankings in each alternative that have less discrimination.
- The proposed "cost of uniformity" metric provides an approach to determine which of the alternatives would be the closest to the overall average score of the spatially diverse solution obtained from the fuzzy, spatial MCDA approaches.
- The impact of inserting additional criteria into the MCDA showed significant differences between different numbers of applied criteria. It shows clearly that additional criteria give more diversity of options.

5.2 Contributions

Specific key contributions made by this dissertation include the following:

- Provide comprehensively reviewed research on GIS for integrating surveyed cross-section data with lower accuracy DEM, and offer insights into the advantages and limitations of various MCDA techniques for evaluating flood damage reduction alternatives.

- Produce adjusted DEM's by combining an unadjusted DEM with existing surveyed stream channel elevation data. The adjusted DEM's also represent the general landscape and are comparable in quality to aerial photogrammetry. These will provide measurable improvement in floodplain mapping for use with MCDA techniques and give the decision maker the capability to better decide the preferred flood damage reduction strategies.
- Present the development of a GIS-based MCDA interactive model that is transparent and easy for a decision maker to use. This provides an automated process of alternative evaluation and selection within a flexible, fully integrated interactive system. By graphically presenting the results of each simulation, the implications of each alternative can be easily understood.
- Showed that among MCDA methods for flood management purposes, the spatial fuzzy approach method gives the most diversity in the flood damage reduction alternatives. The performance of the ISFWAM method coupled with an adjusted DEM in a GIS environment is compared with other commonly used MCDA techniques. This research showed how this approach improved the capability to show greater diversity and greater spatial distribution of the best alternatives.
- Demonstrated the impact of adding additional MCDA criteria. Current research shows MCDA for flood damage has been applied using only a few criteria (only flood water depth and flood damage) but for better results the MCDA approach needs to apply more criteria for evaluating the alternatives. By adding additional criteria into MCDA, the capability to make the best alternatives more diverse and

show the decision maker more differences in the scores of the alternatives to allow the decision maker to discriminate is significantly improved.

- Proposed the development of a "cost of uniformity" metric that allows decision makers to compute the impact of selecting a single alternative for the entire floodplain. This metric represents the increase in the average distance metric value as compared to the spatially diverse solution from the MCDA and GIS analysis.

5.3 Recommendation for future research

Based upon the analysis described in this research, many other aspects and issues are suggested for further research.

First, there are issues beyond the analysis done in this study such as economic considerations and analysis that may be incorporated into the GIS-based MCDA interactive model for its practical use.

Second, one of the future research directions is the implementation of different fuzzy membership functions that might be assigned to criteria, parameters, and weights, thus potentially improving the evaluation of the alternatives.

Third, the GIS-based MCDA interactive model explored in this research is a good tool to find which MCDA methods are preferred for evaluating candidate alternatives. The developed MCDA model could be applied extensively to show its strength in practical floodplain management, since it is possible to evaluate the alternatives automatically based upon many other objectives as well. Applicability of the developed model does not restrict the user to only floodplain management purposes. It can easily be applied to any other complex decision-making processes that need to be carried out spatially and has some vagueness and imprecision involved (Nirupama and Simonovic 2002).

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