A GIS APPROACH TO MULTI-CRITERIA DECISION MAKING:

Floodplain Analysis of the Red River Valley

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
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IN
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by:

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A GIS APPROACH TO MULTI-CRITERIA DECISION MAKING FLOODPLAIN ANALYSIS OF THE RED RIVER VALLEY

BY

ROBERT JOHN TKACH

A Thesis/Practicum submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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ABSTRACT

Multi-criteria decision making techniques are often used in the field of water resources. Their function is to facilitate decision making for the purpose of selecting the best solution to a particular problem from a set of potential alternatives. In order to assist in the selection, multi-criteria decision making techniques evaluate each of the potential alternatives. The evaluation is based on an assessment of how well each of the alternatives satisfies specified criteria. These criteria typically are the characteristics of the alternatives, or consequences which would occur due to implemententation of the potential alternatives. Often the measures of the criteria, or criteria values, associated with the alternatives have an uneven spatial distribution. For example, implementation of a particular alternative could produce favorable impacts in one location in a given region, while resulting in negative consequences for other areas. As a result, the best alternative for one area within the given region may not be the best solution for all locations in that region.

In the evaluation of alternatives by conventional multi-criteria decision making techniques this spatial variability in the criteria values is often not taken into consideration. The criteria values used by conventional techniques typically represent the average characteristics of the alternatives, or total impacts produced by the alternatives for the entire region. Thus, in evaluating potential alternatives, the localized characteristics and impacts associated with the alternatives are not taken into consideration. As a result, the alternative selected as best using the multi-criteria decision making techniques may have significant negative characteristics or impacts in specific areas within the region. This shortcoming in conventional multi-criteria decision making techniques is demonstrated in this study using a floodplain analysis of the Red River Valley near the City of Winnipeg, Manitoba, Canada. In this study a set of potential flood protection alternatives are generated for a region within the Red River Valley. Each of the potential alternatives in the set are evaluated and ranked on the basis of multiple criteria. The

criteria used in this evaluation are impacts to the region produced by flooding which would occur with implementation of each of the various alternatives.

The evaluation of the alternatives is conducted using two multi-criteria decision making techniques. First, the alternatives are evaluated and ranked using the Compromise Programming technique. In this evaluation the spatial variation in the criteria values associated with the alternatives is not considered. The second multi-criteria decision making technique used in this evaluation was the Spatial Compromise Programming technique. This new technique was developed as part of this research by combining GIS technology with the Compromise Programming technique. Using the Spatial Compromise Programming technique it was possible to account for spatial variability in the criteria values used in the evaluation of the potential flood protection alternatives. By comparing the results of the two multi-criteria decision making techniques it is shown that the spatial variation in the criteria values must be taken into consideration in order to provide an accurate evaluation of the potential alternatives.

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LIST OF DEFINITIONS

Alternative:

- a potential solution or project which may be implemented for the purpose of solving or mitigating a particular problem

Criteria:

- a physical, biological, economic, or other characteristic or attribute of the alternatives that the decision makers consider important
- a characterizing mark or trait; standard or evidence on which a decision or judgement may be based
- a basis for a decision that can be measured and evaluated

Criteria Value:

- the measure, or magnitude, of the criteria for a given alternative

Digital Elevation Model (DEM):

- a raster image which describes the continuous variation of the ground surface elevation

1. INTRODUCTION

Selecting the best strategy from a number of potential alternatives in water resources planning and management is a complex decision making process (Bose and Bose, 1995). This complexity is typically the result of multiple, and potentially conflicting, criteria of one or more decision makers, and the difficulties associated with combining and comparing both quantitative and qualitative criteria. The decision making process can benefit from the use of multi-criteria decision making (MCDM) techniques. These techniques can be used to facilitate decision making by making the process more explicit, rational, and efficient (Hobbs et al., 1992). This is accomplished by the MCDM techniques based on their ability to apply the decision makers' preferences towards criteria associated with the potential alternatives in a consistent, systematic and unbiased manner.

Conventional MCDM techniques can be used to evaluate alternatives and ultimately identify the best solutions based on the criteria values associated with each of the alternatives, and the objectives and preferences of the various decision makers. The criteria, which may be quantitative and/or qualitative and in nature, represent the potential positive and negative characteristics and implications of each alternative for the region under consideration as a whole.

Often the consequences resulting from implementation of an alternative are not evenly spatially distributed. Thus while an alternative may be beneficial for one location it may incur negative impacts for another. Unfortunately conventional MCDM techniques do not accommodate unequal spatial distribution of the criteria values in the determination of the best alternative. Consequently the alternative which emerges as best for the entire region through the process of evaluation may not be the best alternative for all individual locations within the region.

The purpose of this research was to develop a spatial MCDM technique which could capture the spatial distribution of the criteria values associated with the various alternatives. This MCDM technique would have the advantage over conventional MCDM techniques in that it could be used to identify the best alternative for each location within the region under consideration. This information can be used to assist decision makers in selecting the best alternative from a set of potential solutions to a particular problem. The new MCDM technique developed in this research was created by combining the existing MCDM technique Compromise Programming with Geographic Information System (GIS) technology.

Compromise Programming (Zeleny, 1973) is a MCDM technique which can be used to identify the best solution to a particular problem from a set of potential alternatives. Evaluation of the alternatives by this MCDM technique is based on the criteria values associated with the potential alternatives, the relative importance of the criteria to the various decision makers, and the significance of the maximum deviation of the criteria values from their ideal magnitude (Simonovic, 1989).

Geographic Information Systems are a rapidly evolving technology which can be used for the efficient storage, analysis, and management of spatial information. As analyses in water resources inevitably require the analysis of spatial information, GISs have found application in this field. For decision making in the field of water resources, GISs have predominantly been used to determine suitable geographic locations for alternatives based on an analysis of various criteria. The conducted research for this study took reverse approach and used a GIS to determine the best alternative for each location in a given region.

A spatial MCDM technique was developed by combining the Compromise Programming technique with GIS technology. For purposes of this thesis, this new technique is referred to as Spatial Compromise Programming. GISs have the ability to capture the spatial variation of the criteria values associated with a set of potential solutions, or alternatives, for a specific water resources problem. The criteria values associated with each alternative, for each location within a given region, are determined using a GIS. The potential alternatives are evaluated by comparing the criteria values for each location, between the alternatives. Evaluation of the alternatives is performed by embedding, or applying, the Compromise Programming technique within a GIS framework. Through application of the Spatial Compromise Programming technique it is possible to identify the best alternative, from a given set, for each location within the geographic region under consideration.

The analysis of potential floodplain management strategies for the Red River valley near the City of Winnipeg, Manitoba, Canada was chosen as a case study to demonstrate application of the Spatial Compromise Programming technique. A floodplain analysis model was developed in order to analyze potential floodplain management strategies for the Red River valley. The model was first used to generate a set of potential flood protection alternatives for the case study area and to simulate flooding based on their implementation. This was accomplished by combining GIS technology with a conventional hydraulic model. The floodplain analysis model was then used to determine the impacts caused by flooding which would occur within the Red River Valley under implementation of the potential alternatives. These flood water impacts were used to evaluate and rank the potential flood protection alternatives using both the Compromise Programming and Spatial Compromise Programming techniques. Through application of the Compromise Programming technique the best alternative, from the potential set, for the entire region was determined. The best alternative for each location within the case study area was determined using Spatial Compromise Programming. By comparing the alternative rankings produced through application of the two MCDM techniques the merits of the Spatial Compromise Programming technique were identified.

Contained in this thesis is a description of the research performed towards the development, simulation, and evaluation of potential flood protection alternatives for the case study. Chapter 2, contains a discussion of the use of GISs in the field of water resources. In many past analyses GISs have been used in connection with, or as a replacement for conventional water resources models in order to enhance their capabilities. The main enhancement provided by GISs are the capacity to process the spatial information which is often required in water resources analyses. This Chapter begins with a description of specific uses of GISs for water resources modelling, planning and management, and decision making. The Chapter concludes by describing the different levels at which GISs have been used with conventional models in past water resources analyses.

Chapter 3 begins with an overview of the development and evaluation of flood control alternatives. A detailed description of the floodplain analysis model used in the case study follows. This model was developed by linking GIS technology with a traditional hydraulic model. Also included in this Chapter is a description of the input required by the floodplain analysis model. The enhancement to the hydraulic model provided by the GIS, is discussed in detail. Finally the methods by which flood protection alternatives can be generated and evaluated using the floodplain analysis model are presented.

Chapter 4 provides a description of the MCDM technique Spatial Compromise Programming. The Chapter begins with an overview of general issues pertaining to decision making in the field of water resources. A description of the traditional MCDM technique Compromise Programming follows. Through use of an example, the shortcomings of this approach with respect to incorporating spatial considerations in decision making are presented. A description of the Spatial Compromise Programming approach follows. By applying this technique to the same example, using GIS technology, spatial aspects are incorporated into decision making.

Chapter 5 describes the case study used to demonstrate the Spatial Compromise Programming technique. In this Chapter both the previously discussed floodplain analysis model and Spatial Compromise Programming technique are applied to a specific water resources problem. The selected case study was the floodplain analysis of the Red River Valley. The specific geographic region being investigated, as well as the present level of flood protection provided to the area are described first. The generated set of flood protection alternatives used in the case study are described next, followed by a review of the criteria in which evaluation the flood protection alternatives was based. The flood water impacts associated with the implementation of each of the potential alternatives are determined by the floodplain analysis model. Based on these impacts the alternatives are first evaluated using Compromise Programming and then Spatial Compromise Programming. The Chapter concludes with a discussion and comparison of the results of the two methods.

Chapter 6 presents conclusions based on an analysis of the case study and recommends future research directions.

2. ROLE OF GIS TECHNOLOGY IN WATER RESOURCES

Geographic Information Systems are the combination of computer hardware, software, and databases containing spatially distributed information. Their functional purpose is to link real world objects in terms of: a) their position with respect to a known coordinate system; b) their qualitative and quantitative characteristics; and c) their spatial and temporal interrelations with other objects (Burrough, 1993). While paper maps have been the historical form used to store this data, the advent of digital maps and GISs provide alternate methods to input, edit, store, display, analyze, and output spatial information (DeVantier and Feldman, 1993).

2.1 GIS ANALYSIS OF WATER RESOURCES

GISs are a rapidly evolving technology which have found application in many fields of study including the field of water resources. GISs have been applied extensively in water resources analyses for purposes such as modelling, planning and management, and decision making. In these analyses GISs have been used for many different purposes which have ranged from parameter determination and data preparation for use in conventional models, to the actual simulation of water resources systems. The application of GIS to water resources issues has benefited their analysis in many ways. There are two key justifications for applying GISs in the field of water resources which include: the dependence of water resources issues on spatial information; and the visualization capabilities of GISs.

Virtually all analyses in the field of water resources require the use of spatially distributed information. This data could range from general topography of the earth's surface to land use types, and the locations and descriptions of man-made structures. Uses of and specific requirements for this spatial information are dependent on the type of analysis which is being performed. For example, modelling of surface water runoff requires information such as land use type, channel length, roughness, and other sub-basin characteristics in order to describe the watershed being modelled. Often this information is spatially variable across the study region. Based on the spatial nature of these parameters, the use of a tool whose key function is the management and manipulation of spatial information for their analysis is only logical. Consequently GISs are frequently used for processing the spatially variable information which is often required in the analysis of water resources.

If a picture is worth a thousand words, the application of GISs in water resources analyses has infinite value. Based on its visualization capabilities GISs have enhanced the analyses of water resources in many ways. Through its graphical interface GISs facilitate understanding of the spatially distributed information required as input, or produced as output through analyses of water resources. Conventional forms of analyses have required that spatially related inputs and outputs be stored, manipulated, and inspected in text format. By viewing this information graphically the level of comprehension of what it represents is increased, and misinterpretation of analysis results is reduced. This ultimately leads to better overall management of water resources.

These are just two of the more common benefits of applying GISs in the field of water resources. A discussion of applications of GIS in water resources analyses pertaining to modelling, planning and management, and decision making follows. Some of the more common ways in which GISs are applied to each type of analysis are outlined. A detailed description of a situation in which a GIS was used to facilitate each specific type of analysis, is also provided. The application of GISs to water resources modelling, planning and management, and decision making described takes the form of a three level hierarchy. At the first level, specific tasks for which GISs have been used to facilitate the modelling of water resources are described. The next level provides a discussion of how GISs have been applied to water resources planning and management. Planning and management often requires the use of multiple water resources models, and an analysis of their combined output. Thus all tasks performed by GISs for the purpose of modelling, in addition to those specific to planning and management, are encompassed in this level. Finally, the third level of the hierarchy describes how GISs can be used in water resources decision making and the development of spatial decision support systems. Water resources are often modelled as a prelude to their analysis for the purposes of planning and management or decision making. In this third level of the hierarchy it is assumed that decision making in water resources requires all information generated in analyses for modelling, and planning and management. Thus just as the second level encompasses the first, all GIS tasks involved in modelling as well as planning and management are included in the decision making level.

2.1.1 MODELLING

GISs have been successfully used in the past for the purpose of modelling or to facilitate modelling in the field of water resources. Past experiences have predominantly pertained to ground-water hydrology but have also included surface-water analyses. These studies have encompassed the modelling of both water quality and water quantity. Some of the more common applications for which GISs have been used in modelling include parameter determination, data preparation for conventional water resources models, visual display of spatial input and output for observation, simulation of water resources, characterization of hydrologic trends, and response prediction to water resources related events.

A sample application of a GIS in the modelling of water resources is illustrated in the work of Ross and Tara (1993). The purpose of this study was to evaluate impacts on the hydrology produced by phosphate mines, for areas surrounding their location. The software which was linked together to perform this task included the GIS SPANS, the surface-water model HSPF, the ground-water model MODFLOW, and an evapo-transpiration model ET. In this analysis the GIS was used primarily to develop input for hydrologic models as well as to provide linkage between models with different spatial representations, or georeferencing. The surface and ground water parameters of the region were determined by applying the spatial analysis capabilities of the GIS on digital maps containing the physical characteristics of the study area. This data was then exported from the GIS database to external files formatted for input into the actual surface and ground water models. After the hydrologic simulation and analysis had been performed the GIS was also used to display output graphically.

Other good illustrations of the benefits of applying GISs to modelling of water resources are found in recent papers by Giammarco et al. (1994), Baker et al. (1993), Shea et al. (1993) as well as Djokic and Maidment (1993).

2.1.2 PLANNING AND MANAGEMENT

The planning and management of water resources involves the analysis and implementation of structural and non-structural measures in order to meet present and future water demands based on observation of existing and potential supplies (Loucks et al., 1981). These water demands and supplies may be qualitative and/or quantitative and often reflect the perspectives and objectives from multiple disciplines (e.g., engineering, social, economic, environmental, management) and stakeholders.

Planning and management can be described as the application of multiple water resources models and the analysis of modelling output for a purpose greater than could be addressed by any of the individual models alone. Modelling thus described can be viewed as a preliminary step in planning and management. The need for multiple models arises for a number of reasons. In contrast to modelling, analyses for the purpose of planning and management typically encompass a larger spatial and temporal scale, and multiple resources and purposes are often considered. Under these circumstances each model used may represent individual small portions of the larger space, time, resources and purpose being considered overall.

GISs are an effective tool for planning and management in the field of water resources. Immense volumes of data are often involved in analyses for purposes of planning and management. As a result the need for efficient management of spatial and non-spatial data is critical. The combination and organization of output produced by water resources modelling, required for analysis in planning and management, is an ideal task for GISs. GISs can also be used to analyze this information. Specific planning and management tasks for which GISs may be of assistance include comparative analysis, monitoring of dynamic processes, evaluation of current conditions, detection of changes, forecast of future developments, problem assessment, planning of actions (e.g., mitigation), identification of regions that meet multiple criteria (e.g., site selection), identification and allocation of resources, analysis of policy options and the determination of cumulative effects based on spatial location (Kaden, 1993).

An application of the use of a GIS in water resources planning and management is found in Keser and Bogardi (1993). The purpose of this study was to develop a national water resources master plan, based on existing and predicted future conditions in the country of Tunisia. The country was divided into 188 administrative units and for the purpose of this analysis, 40 hydrologic units or watersheds. A GIS was selected as an ideal tool for use in this study based on the large scale of the project, and the required analysis of spatially and temporally variable data. The GIS was used first to aggregate water resources demands and supplies based on political and hydrologic subunits. Water surpluses and deficits for each political and hydrologic unit were calculated using the GIS. Water balances were determined for each political unit based on existing and future conditions. The GIS was used to identify hydrologic units with water surpluses which could feasibly and efficiently provide assistance to regions with water deficits, based on spatial location. Finally, the GIS was used to display all spatial information throughout all phases of the project graphically.

Other applications which demonstrate the ability of GIS to facilitate planning and management in the field of water resources can be found in Meyer et al. (1993), McKinney and Maidment (1993), and Shamsi (1996).

2.1.3 DECISION MAKING

In order to address a specific water resources problem, typically a number of potential alternatives are available. Decision makers are required to select and implement the best solution to the problem from the set of potential alternatives. Selecting the best alternative is a complicated process due to having to take many criteria, constraints, and interests of different decision makers into consideration. In the past, decision makers have relied on mathematical models to assist them in generating, evaluating, and selecting alternatives. Implementation of these models often required technical skills that decision makers simply did not possess. This led to misuse of the models, a lack of understanding of their output, and subsequently misinformed decision making. Thus came the need for, and the birth of Decision Support Systems.

A Decision Support System (DSS) is an interactive combination of technologies designed to assist in the decision making process (Loucks and da Costa, 1991). DSSs are comprised of four main components which include a model-base, data-base, system manager and user interface (Simonovic, 1993a). The model-base is comprised of conventional water resources models needed to perform analyses of a given problem. The data-base component is responsible for data storage and manipulation and typically consists of an efficient database management software. The system manager component facilitates and coordinates interaction between the various technologies. An Expert System is a commonly used for this task. The user interface is that component of the DSS with which the decision maker interacts. The key component of the DSS, the interface is responsible for accepting user requests for information and for providing useful, understandable, and reliable feedback. The assembly and application of these components facilitates the decision making process by providing the decision maker with increased comprehension of the given problem.

Geographic Information Systems on their own could be considered as very basic DSSs because in general they possess the same components. The model-base of the GIS is represented by its analysis and modelling capabilities. The database component is comprised of digital maps containing spatial information which may be input, stored, manipulated, and output by the GIS. Most GIS packages have an interface through which the user can display, query and change spatial data contained in the database. However, the combined capabilities of these components would provide very limited decision support in water resources. First the limited analytical capabilities of GISs are very limited in comparison to conventional water resources models. Secondly, most GIS databases do not have the ability to store and manipulate non-spatial information which is often used in water resources analyses. Finally, though GISs often have an interactive user interface its use often requires knowledge of the software which decision makers might not possess. As a result, though they have the components necessary to construct a DSS, on its own a GIS would produce an ineffective DSS.

The addition of a GIS to the model-base, database, and user interface components of a conventional DSS would be beneficial. Its main contribution to the DSS would be the addition of a spatial database, and the ability to analyze and display spatial information (Furst et al., 1993). The combination of a GIS with a conventional DSS has been called a Spatial Decision Support System (SDSS). SDSSs are ideally suited for use in the analysis of spatial information related to water resources problems (Walsh, 1993). As this combination of technologies is still relatively new, few SDSSs have gone beyond the conceptual stage (Watkins et al., 1996). As a result it is difficult to describe specific or distinct tasks or roles of GISs in SDSSs based on past experiences.

A sample application in which a GIS was combined with an Expert System for the purpose of enhancing the decision making process in water resources management is found in McKinney and Maidment (1993). The purpose of this study was to test the ability of an expert GIS for developing long-term water supply alternatives. Given existing and projected water supplies and demands, the system developed determined potential water deficits and surpluses for the Corpus Christi region in Texas over a 50 year planning horizon. Given a projected water deficit, the system suggested efficient alternatives for developing additional water supplies. The system was composed of a GIS, Expert System, database management system (DBMS), and various data computational and conversion programs. The GIS was used to store and manipulate spatial information. Specific tasks included determining the location and magnitude of water demands and supplies. The Expert System played two major roles in the project: first, it acted as a master controller by directing and integrating the GIS, DBMS and other external programs; secondly, it was used to evaluate and select the most suitable water supply development alternative from a set of options, given a projected water deficit. Evaluation and selection was based on an objective to minimization cost. According to the authors, the expert GIS is still in an early development stage and is but a part of a much larger project for regional water resources planning.

2.2 TYPES OF GIS MODELS

The application of GISs in water resources analyses is a function of the type of analysis being performed. In the analyses described in Section 2.1, GISs were used in connection with conventional water resources models. As a result, the exact role of the GIS in each case was dependent on its level of interaction with the conventional model. The application of GISs in the modelling of water resources can be categorized according to three basic levels: 1) GIS linked models; 2) GIS integrated models; and 3) GIS embedded models (Watkins et al., 1996). A discussion of these three model types, in their application to water resources modelling, follows.

2.2.1 GIS LINKED MODELS

Linked models are a combination of GIS technology with conventional water resources models. In this combination the principle role of the GIS is to provide support for the component which is actually performing the modelling. Typically this support is in the form of data storage and manipulation, preparation of input to the model, as well as graphical display of the modelling results.

In order for the linked model to function as a whole, its separate components must be able to transfer information to and from one another. Due to differences in the technologies, however, many conventional water resources models cannot directly use data as produced by the GIS, and vice versa. This incompatibility is due to the fact that the classical models do not account for the spatial dimension in their input, analysis, and output to the same extent that GIS can (Walsh, 1993). As a result, the data must be transformed or averaged spatially to the level required by the classical models. This transformation can be accomplished manually, or through the use of external data conversion programs. In so doing, much of the data's spatial variability is lost. Quite often information produced by the GIS is degraded to such an extent that in order to be usable by conventional models it must be stored in separate databases. The degradation of spatial variation in data prepared by the GIS for use by the water resources model is one of the characteristics of a GIS linked model.

The components of a GIS linked model are connected for the purpose of data transfer but both the GIS and water resources model still have the ability to function independently. In addition, as shown in Figure 1, there is typically no common user interface for the entire model. As a result the user must interact with each component separately. This is the final major identifying characteristic of a GIS linked model.

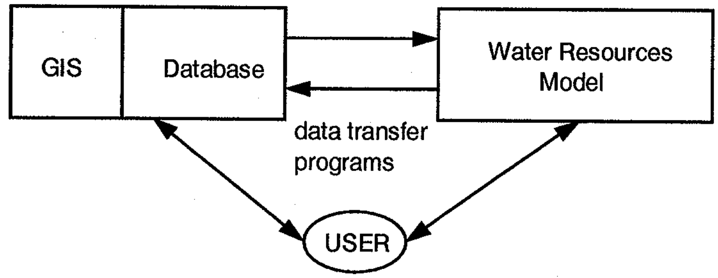

Figure 1: GIS Linked Water Resources Model (after Watkins et al., 1996)

An excellent example of a GIS linked model is the combination of the urban storm-water model RUNOFF with the IDRISI GIS package by Meyer et al. (1993). The purpose of this study was to evaluate various storm-water management strategies based on calculations of urban runoff depths and discharges. In this example the GIS was used to facilitate the preparation, examination, and analysis of spatially distributed inputs and parameters for the storm-water runoff model. In exchanging information between the model components, however, difficulties arose due to dissimilar file formats. Input for the RUNOFF model did not require the level of spatial variability that the GIS could provide. As a result, utility programs were required to "average" the information spatially across the hydrologic subunits in order to convert it into a format suitable for input to the storm-water model. Output from the runoff model was also processed by the GIS so that it could be examined by the model's user. In this application of GIS for evaluation of water resources strategies the model components were linked for the purpose of data transfer but both were operated independently by the user.

2.2.2 GIS INTEGRATED MODELS

A GIS integrated model may be described as a very strongly linked model (Watkins et al., 1996). Based on this, the use of an integrated model is essentially the same as a linked models described in Section 2.2.1. Due to the considerable subjectivity inherent in measuring the bonds between model components, differentiating between GIS linked and GIS integrated models is often difficult. The strength of the link can be measured on the basis of the level of user interaction with the overall model, and the extent to which the spatial variability in the data is reduced. Ideally, in the case of a GIS integrated model the user will interact only with the water resources model or with the GIS. In addition, both the GIS and the water resources model components share the same database, whether it is the GIS database or an external one. By using a common database the spatial variability of the data is not lost due to averaging as in the case of GIS linked models. Typically the water resources model and the GIS components are connected to a common database by using various data transfer programs which are executed in the background. The architecture of a GIS integrated model is shown in Figure 2.

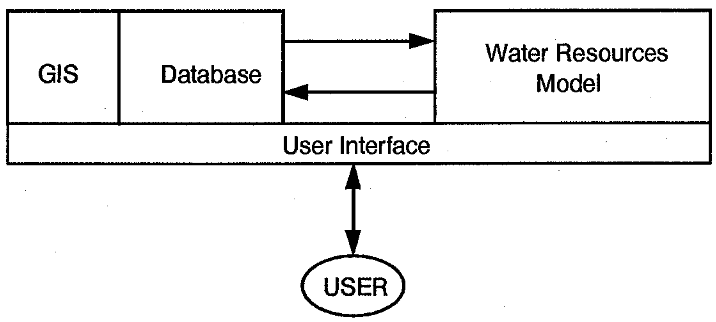

Figure 2: GIS Integrated Water Resources Model (after Watkins et al., 1996)

An example of a GIS integrated water resources model is the storm-water management model produced by Shamsi (1996). In this example, the CPSRM runoff model is integrated the with Arc/Info and ERDAS GIS packages. The storm-water modeling is performed using the runoff model, while the two GISs are used once again, as in the linked models, for data preparation and parameter determination. The strength of the linkages between the technologies, making this an integrated model, is determined by the choice of the runoff model. The CPSRM model is a lumped parameter runoff model which includes a built-in database and GIS interface. Based on its common database and interface, the user can interact with the storm-water management model without having to communicate with each component of the GIS integrated model separately. This satisfies the first requirement of an "integrated" model. As CPSRM is a lumped parameter model, it requires averaged values of parameters in order to perform runoff modelling. The requirement for averaged data by the CPSRM model detracts from the overall model as being an integrated model. However, in Shamsi's study special attention was given to ensuring that all subbasins in the study area were as small as possible. As a result the runoff model appeared indistinguishable from a distributed parameter model. Little of the spatial variability of the data required by the model was lost. In this way, both requirements for an "integrated" model were satisfied.

2.2.3 GIS EMBEDDED MODELS

GIS embedded water resources models represent the most elite use of GIS in water resources modelling. In this type of model the GIS is used to actually perform the analysis which is normally done using a conventional water resources model. Also the GIS is used for data preparation and parameter determination. With embedded models the user interacts solely with the GIS through the existing GIS interface or through a constructed interface specific for the type of modelling being done. A schematic of a GIS embedded water resources model is shown in Figure 3. Embedding water resources models within a GIS can be accomplished either by: 1) using the existing modelling and analytical capabilities of the selected GIS software; or 2) creating new GIS modules capable of performing the desired operations on the spatial database.

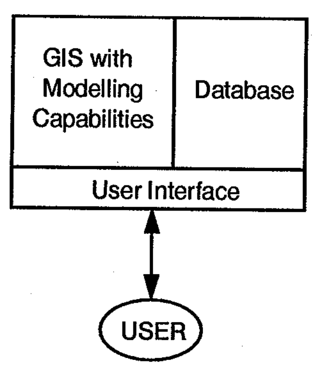

Figure 3: GIS Embedded Water Resources Model (after Watkins et al., 1996)

Presently GIS embedded models are the most uncommon of the three model types. This is because most GIS systems do not provide the necessary analytical capabilities required, and currently available in conventional water resources models. The greatest limitation of GIS analyses is the inability to model the fourth dimension, i.e., time (Maidment, 1991). This is an ability which is required in order to perform most water resources modelling.

An example of an embedded water resources model within a GIS is the groundwater model developed by Batelaan et al. (1993). This GIS embedded water resources model was comprised of the GIS software GRASS and a specially written groundwater program. The GIS embedded model was used to simulate groundwater recharge and discharge as well as to construct groundwater elevation maps. Computations performed by the groundwater program made maximum use of GRASS built-in operating functions. The groundwater program itself was embedded within the GRASS software and was executed as a GRASS command. All input and output data were stored and manipulated in the form of raster images. Interaction with the embedded model was through the GRASS interface.

In the research presented in this thesis, a GIS was used to facilitate two types of water resources analyses. These analyses were performed by the floodplain analysis model described in Chapter 3. The floodplain analysis model consisted of two components: a GIS; and a conventional hydraulic model. The first analysis performed using the floodplain analysis model was the generation and simulation of a set of potential flood protection alternatives for the case study area. In this part of the floodplain analysis the GIS was used in combination with the conventional hydraulic model. With respect to the different model types discussed in Section 2.2, this is an example of a GIS linked water resources model. By using GIS in connection with a conventional hydraulic model the combined capabilities of the two technologies exceed that of either component alone. The second analysis performed using the floodplain analysis model was the evaluation of the generated set of potential flood protection alternatives. This portion of the floodplain analysis was performed using the analysis capabilities of the GIS alone. The best alternative from the potential set was also identified by the floodplain analysis model. Evaluation of the alternatives was facilitated by implementing the Compromise Programming, and Spatial Compromise Programming multi-criteria decision making techniques. Implementation of the Spatial Compromise Programming technique was accomplished using the analysis capabilities of the GIS. With respect to the different model types discussed in Section 2.2, this is an example of a GIS embedded water resources model. A description of the procedures necessary to embed this technique with the GIS framework are discussed in detail in Chapter 4. The actual application of GIS in the generation, simulation, and evaluation of the flood protection alternatives for the case study is discussed in Chapter 5.

3. FLOODPLAIN ANALYSIS MODEL

The case study selected to demonstrate the capabilities of Spatial Compromise Programming technique was the floodplain analysis of the Red River Valley region near the City of Winnipeg, Manitoba, Canada. As a result a model capable of performing a floodplain analysis of the area was required. The floodplain analysis model would be used to: generate potential flood protection alternatives for the case study area; simulate floods of specified magnitudes and determine the flooding impacts which would occur given implementation of the alternatives; and evaluate the potential alternatives.

This Chapter describes the floodplain analysis model used to generate and evaluate potential flood protection alternatives for the case study area. The Chapter begins with a general overview of issues considered in the development of flood control alternatives. A discussion pertaining to the development and preparation of the floodplain analysis model used in the case study follows. First is a description of the individual components of the floodplain analysis model. Next, the input required by the floodplain analysis model is described. The Chapter concludes with a description of how the model components are used together to: simulate flooding; generate potential flood protection alternatives; and determine the flooding impacts which would occur given implementation of the potential alternatives.

3.1 OVERVIEW

Flood simulations are performed in order to provide qualitative and quantitative information regarding the impacts which could potentially be produced by flooding events (United States Army Corps of Engineers, 1988). The information provided by the simulations includes the magnitude and type of impacts which could be produced by flood waters, as well as the geographic locations in which they would be incurred. Through simulation it is possible to investigate the potential for designing, implementing, and evaluating specific projects whose purpose is to reduce the impacts produced by flooding. These projects are referred to as flood protection alternatives.

Flood protection alternatives are designed to reduce the risk and damages associated with flooding, to an acceptable level. Often the term flood protection is somewhat misleading, as it implies that the project will ensure zero damage and eliminate all risk of flooding (Simonovic, 1993b). However, complete elimination of all hazards or potential for damage caused by high water levels or discharges is seldom possible. Thus the term mitigation is often used, in place of "protection", when referring to the various projects designed to reduce flood impacts.

Flood protection alternatives are typically comprised of combinations of measures which are designed to influence the attributes of an impending floodwave, and the impacts which it produces. These mitigation measures may be either structural or non-structural in nature. Structural measures are used to reduce flood impacts by altering the attributes of the flood wave by changing the physical characteristics (i.e., hydraulic and hydrologic) of the floodplain itself. The physical characteristics of a floodplain, whether natural or man-made, have a direct impact on the attributes of a flood wave. These flood attributes include the magnitude and geographic confines of the flood-wave, its time to peak, and the frequency with which it may occur (United States Army Corps of Engineers, 1988). By modifying the characteristics of the floodplain it is possible to change the attributes of a flooding event. A change in the attributes of a given flood can result in a modification of the impacts which it produces. Examples of structural flood protection measures include dams, reservoirs, retention ponds, dykes, channel modifications (e.g., channel straightening, dredging, etc.) , and diversions.

Impacts produced by floods may also be reduced through implementation of non-structural measures. Non-structural flood protection measures attempt to directly reduce the damages caused by flooding by lessening the exposure of people and property to flood waters. By lessening the potential for contact with flood waters, the number of people and the extent of property susceptible to damage is decreased. Examples of non-structural flood protection measures include floodplain regulation (i.e., land use control), floodproofing, flood warning, and population relocation.

Flooding events produce many different types of impacts. These impacts often include economic, social, and environmental damages. Economic impacts frequently incurred include damage to public and private property, as well as loss of business due to interrupted operations. The interruption or complete elimination of social and general livelihood activities often results from the necessity to relocate or evacuate people and property due to impending flood waters. Environmental damages to both land and water based ecologies are also frequently caused by the sudden rush of large volumes of flood waters and the pollutants (e.g., sediment, pesticides and fertilizers swept from agricultural land, etc.) which they carry.

Flood protection alternatives are designed to reduce all types of impacts produced by flooding events. Given the task of providing flood protection for a specific area, typically a number of potential alternatives exist. Which alternative is selected to mitigate floods in a specific region is dependent on the alternative's effectiveness at reducing flood impacts. Through simulation it is possible to estimate the decrease in flood impacts that would occur with implementation of each potential alternative. In order to estimate the damages produced by flooding, or the reduction in damages which would occur with implementation of flood control measures, the occurrence and magnitude the damages must be correlated with one or more measurable characteristics of the flood. These characteristics could include depth of flood waters, time of year of flooding, flood water flow velocity, duration of flooding, and/or sediment load (McBean et al., 1988). Damages to specific features located in the floodplain, may be correlated with the magnitude of these various flood characteristics. Thus for a given flood, the total damages incurred by all features impacted by flood waters may be determined on the basis of the magnitude of its characteristics.

The reduction in these damages that would result from implementation of a given flood protection alternative can also be estimated. Given a set of potential protection alternatives it is possible to determine which would cause the greatest reduction in flood impacts. Decision makers then select and implement this alternative to mitigate floods in the specific region being considered.

The preferred method used for determining the amount of damage caused by or expected from a flooding event is referred to as the expected annual damage (EAD) approach (United States Army Corps of Engineers, 1989). This method can be used to determine the potential damage which could occur from specific flood events, and weights the value of this damage with the probability that these events might be exceeded. Flood impacts estimated using the EAD approach are based on the dollar value of damage incurred by flooded structures based on their depth of submergence. The reduction of these damages which would result with implementation of a particular flood mitigation alternative can be estimated by calculating the expected annual damage. The expected annual damage is determined with and without implementation of the potential flood protection alternative. The value of the expected annual damage decreases with implementation of the flood protection alternative. The magnitude of this reduction in flood damage is considered to be the benefit associated with implementation of the potential flood protection alternative (Helweg, 1985). By using the EAD approach in this way the best solution from a set of potential flood protection alternatives can be identified. The reduction in flood impacts, or the benefit, resulting from implementation of the potential alternative is first calculated using the EAD approach. Using this measure of benefits together with the costs of different flood protection measures, the numerous options can be contrasted and compared (McBean et al., 1988). Final selection of the best alternative is normally determined on the basis of an incremental cost-benefit analysis.

3.2 MODEL COMPONENTS

A combination of both a GIS and a conventional water resources model was selected to perform the flood simulation, and to generate potential flood protection alternatives. Though the principle role of the GIS in this study is to evaluate the potential flood protection alternatives with the Spatial Compromise Programming technique, its analytical capabilities with spatial information made it an effective tool to be used for flood simulation and alternative generation.

In order to simulate floods a required function of the floodplain analysis model was the ability to perform hydraulic modelling. This was necessary to estimate the water surface elevations which would result from different flood magnitudes, and the implementation of different flood protection alternates. Unfortunately, due to their limited analysis capabilities, GIS technologies cannot perform hydraulic modelling. This is based on the present inability of GIS to model the fourth dimension, time (Maidment, 1991). As a result, a component capable of performing hydraulic modelling was required in the floodplain analysis model. A conventional hydraulic model was selected for this purpose and used in combination with the GIS in order to perform the flood simulation. Thus a GIS and hydraulic model, including their respective databases, were the two main components in the floodplain analysis model. By combining the two technologies their combined capabilities exceeded that of either component alone.

3.2.1 SELECTION OF MODEL COMPONENTS

3.2.1.1 GIS

The software and operation platform had to be selected before preparation of the GIS component of the floodplain analysis model could commence. Objectives in the selection of the GIS were to maximize potential capabilities while minimizing cost. Based on past experience with GIS it was known that this project would require a large database, and would be computationally intensive. As a result, the initial intent was to select a UNIX platform and a GIS software package such as GRASS (United States Army Corps of Engineers, 1993). Though this platform and software were readily available, there was a strong desire to prove that this type of analysis could be performed using much more affordable IBM-PC technology. It was hoped that using affordable technology would increase the possibility that the model developed through this research would be used in practice by decision makers currently involved in the selection of floodplain management strategies for the region being considered. In this way the research could be viewed as a positive step towards bridging the gap between theoretical research and its practical application.

Based on these criteria the IBM-PC based software IDRISI, version 4.0 (Eastman, 1992) and 1.0 for Windows (Eastman, 1995) were selected to fill the GIS requirement for this project. IDRISI is a relatively new raster-based GIS software which delivers a strong analytical functionality at an affordable cost (Meyer et al., 1993). The software is comprised of over 100 separate, executable modules which are linked together through an interactive menu. The application of these modules to a database provides capabilities which include but are not limited to database query, spatial modelling, image classification and enhancement, statistical analysis, and multi-criteria decision support.

Though IDRISI is a raster-based GIS software, it does include some vector support. The creation of vector files is possible through on-screen digitizing. These files may be overlaid onto raster images for purposes of inspection. In addition, provided with the IDRISI software is the TOSCA digitizing package. Due to limitations of the on-screen digitizing abilities within IDRISI, TOSCA was the tool used primarily for the creation and editing of vector data in this research.

3.2.1.2 Hydraulic Model

The HEC-2 (United States Army Corps of Engineers, 1982) model was selected to perform the necessary hydraulic modelling component of the floodplain analysis model on the basis of its analysis capabilities. This model can be used for estimating water surface elevations for steady or gradually varied flow in natural or man-made channels. The effects on the water surface elevations produced by flow obstructions such as bridges, culverts and weirs may be accounted for in the estimation. The changes in water surface elevations due to the implementation, or elimination of flood protection measures may also be determined. The HEC-2 model is designed to estimate water surface elevations on the basis of the computational procedure known as the Standard Step Method.

3.3 FLOODPLAIN ANALYSIS MODEL INPUT

The floodplain analysis model required a description of the characteristics of the Red River Valley in order to simulate flooding in this region, and to generate and evaluate potential flood protection alternatives. A description of these characteristics were contained in the databases of the GIS and HEC-2 components of the floodplain analysis model. The information contained in these databases would be used as input to the analyses performed using the floodplain analysis model. The following is a brief description of the contents of the GIS and HEC-2 model databases.

3.3.1 GIS

The GIS database was comprised of two distinct types of raster images referred to as feature images and Digital Elevation Models (DEMs). The feature images identified the two-dimensional locations of both natural and man-made features in the Red River Valley with respect to the UTM-14N coordinate system. Each raster cell in the feature images contained a numerical identifier corresponding to the specific feature, located in the coordinate boundaries of that cell. Fourteen different classes of features were distinguished in the feature images. The identifiers and the classes of features contained in the feature images are shown in Table 1. A sample of a feature image from the Red River Valley data set is shown in Figure 4.

Table 1: Feature Classes and Identifier Numbers

Identifier	Feature Classes
0	Background
1	River
2	Lake/Dugout
3	Marsh
4	Dyke/Dam
5	Bridge
6	Rail
7	Road
8	Trees
9	Industrial Buildings
10	Municipal Buildings
11	Residential Buildings
12	Hydroline
13	Parks/Recreation
14	Floodway/Canal

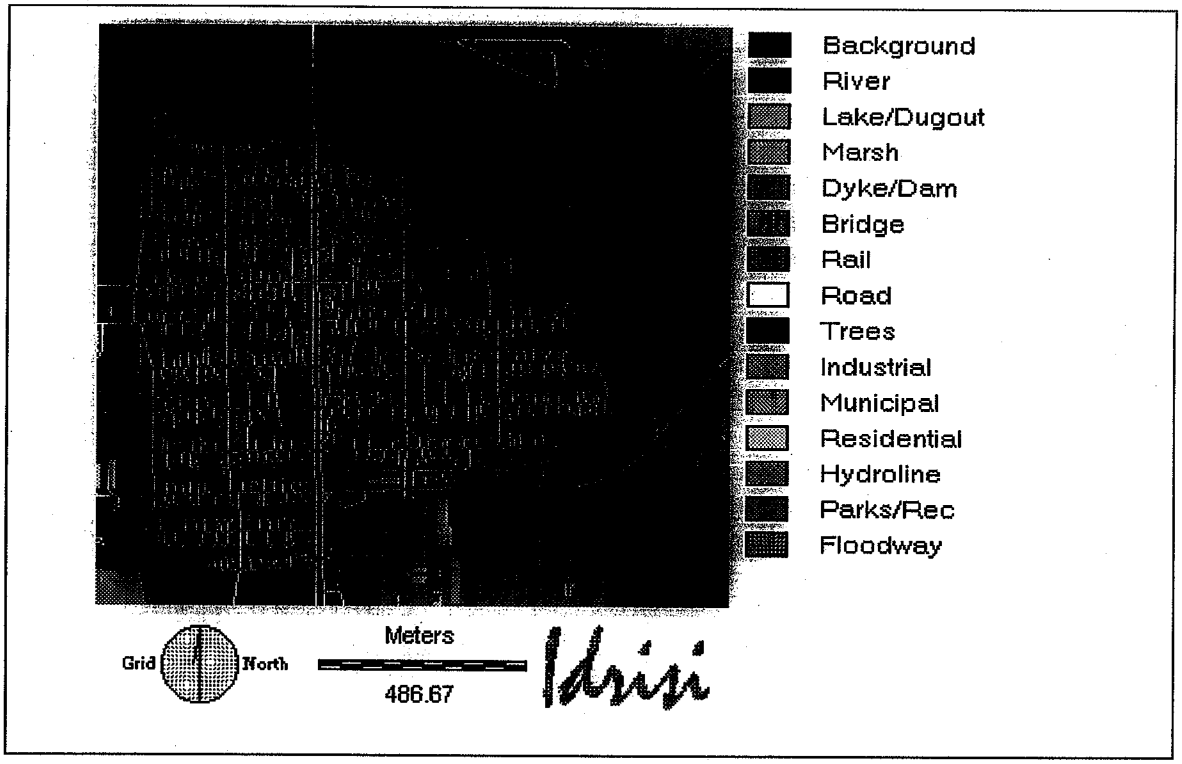

Figure 4: Sample Feature Image for Town of Morris

DEMs in the Red River Valley data set were raster images describing the elevation of the ground surface corresponding to the same locations and reference system as the feature images. Thus for every feature image contained in the data set there was a corresponding DEM. Each raster cell in the DEMs contained a number equal to the ground surface elevation corresponding to location of that cell. A sample of a DEM from the Red River Valley data set is shown in Figure 5.

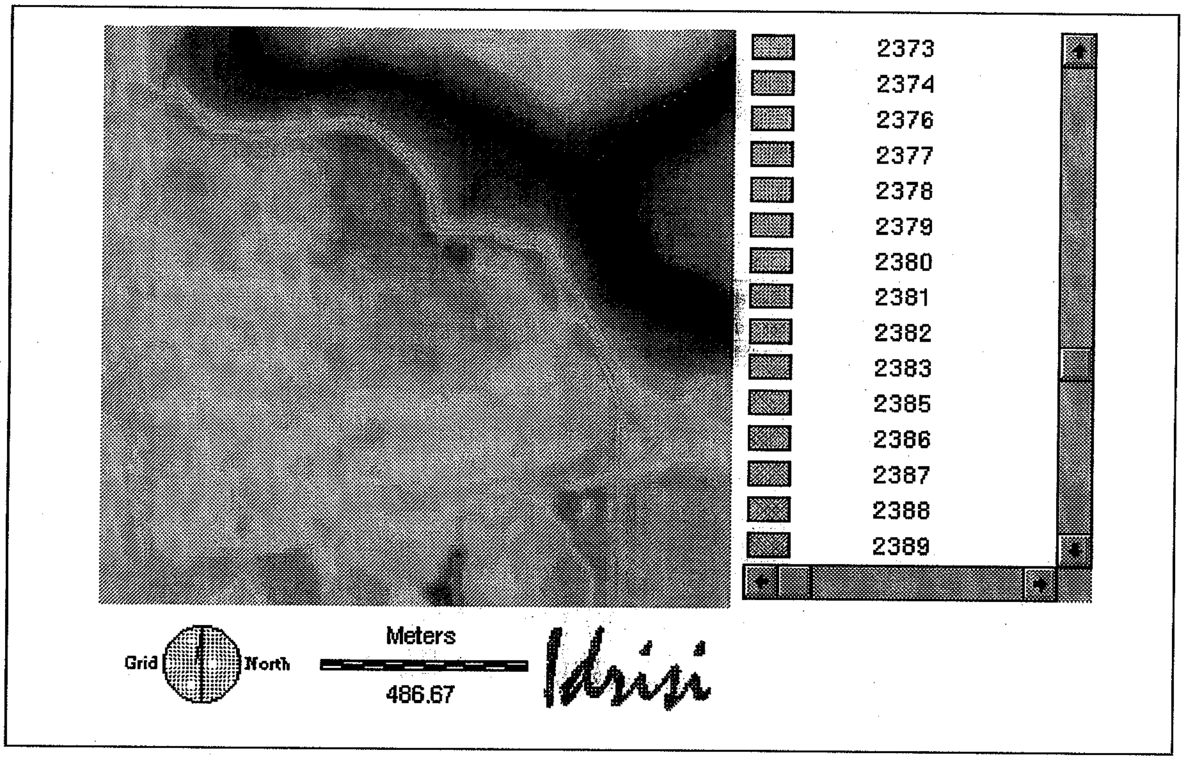

Figure 5: Sample DEM for the Town of Morris

Both the feature images and DEMs contained in the Red River Valley data set were produced by processing information obtained from aerial photos, topographic and contour maps, and conventional land surveying. In order to perform analyses using both the feature images and DEMs, raster GISs require that both image types have the same cell size. Consequently, all feature images and DEMs contained in the Red River Valley database were produced at a cell resolution of 5 m. The steps which were taken to produce the images contained in the GIS database are described in Appendix A

3.3.2 HEC-2 MODEL

The HEC-2 model database was comprised of a specially formatted input file. This file contained a description of the hydraulic characteristics of the case study area and was required as input to the HEC-2 model in order to perform hydraulic modelling. A previously prepared HEC-2 input file, which had already been calibrated on the basis of historic flooding events in the case study area, was conveniently available from the Manitoba Department of Natural Resources. The majority of the data contained in the input file consisted of two-dimensional geographic descriptions of cross-sections of the Red River channel and overbanks. The cross-sections were described on the basis of the coordinate locations of distinct ground elevations of the river channel itself and the channel overbanks. The ground surface elevations describing each cross-section within the HEC-2 input file were a subset of the information used to produce the DEM portion of the GIS database. As preparation of the HEC-2 input file was not directly part of this research it is not discussed in detail in this thesis.

3.4 FLOOD SIMULATION AND GENERATION OF ALTERNATIVES

The following Sections in this Chapter, discuss application of the developed floodplain analysis model for the purpose of generating flood mitigation alternatives for a hypothetical region of interest. The means by which the two model components, the GIS and HEC-2 hydraulic model, were linked together in order to simulate flooding in the region being modelled is described first. The floodplain analysis model can be used to generate and evaluate new potential flood protection alternatives for the region of interest using its ability to simulate flooding. A detailed description of the different alternatives which can be generated using the floodplain analysis model, and the procedures necessary to generate them follows. Next the algorithm used to simulate flooding in the region of interest is outlined. Finally the Chapter concludes with a brief description of a method by which the various generated flood protection alternatives can be evaluated.

3.4.1 MODEL STRUCTURE

A required function of the floodplain analysis model was the ability to perform hydraulic modelling. This would be necessary to determine the water surface elevations corresponding to different flood magnitudes and alternate flood protection strategies for various river sections within the case study area. As previously mentioned, the HEC-2 model was selected to perform the necessary hydraulic modelling. This model computes water surface elevations for distinct segments, or reaches, of the river contained within the region being modelled. Computations are performed based on the geographic and hydraulic characteristics of the river reaches, as contained in the HEC-2 input file, and the magnitude of flooding event.

In addition to determining the water surface elevations for the region of interest, the floodplain analysis model also required the ability to determine the spatial extent of the flood waters, and the flooding impacts. By calculating the water elevations, HEC-2 can determine the spatial extent of the water within the confines of the cross-sections provided in the input file. However, the accuracy and the level of detail provided by the hydraulic model with respect to determining the flood water extent is often questionable. This is because of the low level of detail that the model generally uses to describe each reach. Within any given HEC-2 input file, the only information used to describe any given reach geographically are its upstream and downstream cross-sections. Thus if flooding were mapped based only on this information, the water extent would be represented by straight lines interpolated between successive cross-sections. Based on the lengths of the reaches, this interpolation could be over long distances. As a result the details of the water extent within each reach would be lost. In addition, analysis of the spatial extent of the flood waters within the HEC-2 model is limited. Thus, flood simulation based solely on the use of the HEC-2 model would be insufficient for this study.

GIS was used in combination with the HEC-2 hydraulic model to improve the accuracy of determining the flood water extent. This was accomplished by adding more detail to the reach characteristics provided in the HEC-2 input file using GIS. Given the water surface elevations calculated by the hydraulic model, the GIS was used to determine the spatial extent of the flood waters based on the elevation information contained within the DEMs. By doing so the results of the hydraulic modelling were enhanced. This is because the DEMs provide a more detailed description of the cross-sections of the river channel and overbanks. As opposed to using just a single upstream and downstream cross-section to describe each reach as in the HEC-2 input file, the DEMs describe the cross-sections of the river channel and overbanks in 5 m increments. As described above, using the HEC-2 model the spatial extent of the flood water is determined by interpolating large distances between the successive cross-sections describing each reach. Using GIS to determine the spatial extent of the flood water, the interpolation between successive cross-sections is over much shorter distances. This is because the cross-sections are described by the DEMs on 5 m increments. As a result, details of the region's characteristics that were previously ignored using the HEC-2 model are now taken into consideration using the GIS. In this way, GIS contributes to the determination of the spatial extent of the flood waters.

In order to link the hydraulic model and GIS for the purpose of determining of the spatial extent of the flood waters, a method for communicating between the two technologies was required. Specifically, a linkage was needed to transfer the water surface elevations calculated by the hydraulic model to the GIS. The main difficulty in doing so resulted from the different formats in which the hydraulic model and GIS utilize input and generate output. A method of coordinating the geographic locations of the reaches within the HEC-2 model input file, and the DEMs was necessary. This requirement was met by digitizing the reach information into a new GIS image, having the same dimensions, cell resolution, and georeferencing as both the DEMs and feature images. This reach image showed the length and location of the reaches as contained within the HEC-2 input file. However, by using GIS to determine the spatial extent of the water there existed the potential for the water to extend beyond the confines of the reach cross-sections as contained in the HEC-2 input file. To accommodate this possibility the width of the reaches contained within the GIS image was extended to the image boundaries, perpendicular to the course of the river as illustrated in Figure 6.

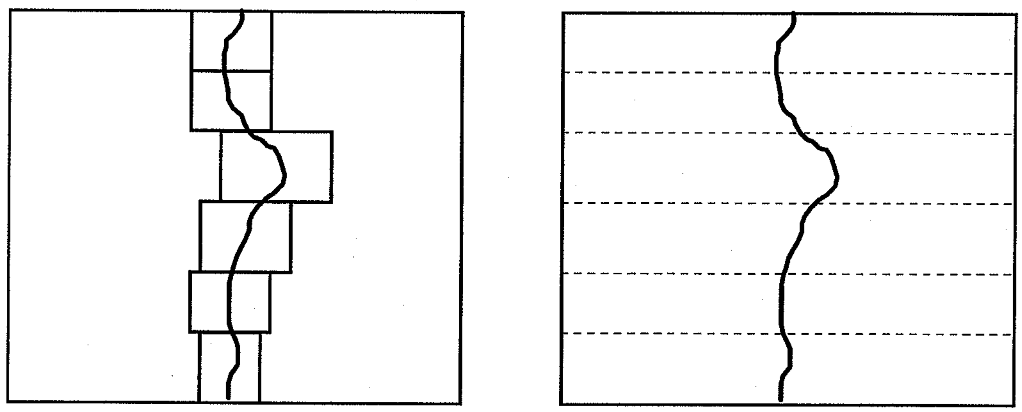

Figure 6: HEC-2 Reaches (left), and GIS Reaches (right)

3.4.2 GENERATION OF ALTERNATIVES

One role of the floodplain analysis model was to generate potential flood protection alternatives for the region being considered. As discussed in Section 3.1, in order to generate flood protection alternatives the characteristics of the region would require modification. Thus the representation of the region's characteristics within the floodplain analysis model required changing. These changes could potentially involve implementation of new structural or non-structural flood mitigation measures, or the alteration of existing ones. As the characteristics of the region were represented within the HEC-2 input file and GIS images, these were the two sources of information in which changes could possibly be made. Contained within the HEC-2 input file is a description of the hydraulic characteristics of the region. This information predominantly consisted of elevations of specific geographic points describing cross-sections of the river channel and immediate overbanks. As discussed in Section 3.3.2 this information was a subset of the elevation data contained within the DEMs used as input for the GIS component of the floodplain analysis model. In addition the GIS database also contained a description of the features associated with the elevation data described by the DEMs.

To generate and ultimately evaluate alternatives it would be necessary to change and analyze the characteristics of the region of consideration. These characteristics would include both the features within the region as well as their respective elevations. Changes in both the features and their elevations for purpose of generating new alternatives could be achieved using the GIS and its database. Similar changes would not be possible within the HEC-2 component of the floodplain analysis model. This is because the features contained in the region were not represented within the HEC-2 input file. Manipulation of the hydraulic characteristics contained within the HEC-2 input file would permit production of a variety of potential flood protection alternatives. However the possibilities for changes in these characteristics within HEC-2 would be limited in comparison to the options available using the GIS with the DEMs. This is because the DEMs contain more elevation information than the HEC-2 input file, spanning a greater geographic area and are described in greater detail. Based on these arguments, it was decided that changes to the region's physical characteristics, necessary for the generation of new potential flood mitigation alternatives, would predominantly be done within the GIS database alone.

3.4.2.1 Limitations in Generation of Alternatives

If changes in the region's characteristics for the purpose of generating flood protection alternatives were to be made only within the GIS database, care had to be taken not to drastically change the hydraulics of the region as represented within the HEC-2 model. Should extensive changes to the topography be made, the hydraulic model would require recalibration if accuracy of the floodplain analysis model were to be maintained. Though recalibration of the HEC-2 model was possible, attempts were made to avoid the necessity of this task. As a result physical changes to the natural and man-made terrain of the region made in the GIS, for the implementation of potential flood control measures, had to be slight. The researcher concluded that for the purposes of this study, alterations in the terrain would be acceptable if they did not dramatically alter the overall quantity of water in the region as determined by the hydraulic model. Alternatives which produced drastic flooding outside the region of interest would not be considered. It was determined further that alternatives causing a change less than or equal to five percent of the overall volume of water in entire region of interest would not require recalibration of the hydraulic model. Selection of the acceptable limit of this change was based on the subjective judgment of the researcher.

To illustrate the limitations in the generation of alternatives, consider the potential construction of dykes on either side of the river being modelled to a height above that of the water surface elevation of the probable maximum flood. An alternative such as this would virtually eliminate flooding in the protected region. Because of the extensive changes in hydraulic characteristics of the region this alternative would require recalibration of the HEC-2 model. Also, an alternative of this sort would reduce the storage of flood water in dyked regions along the river and would likely produce intense flooding downstream. Creation of a flood protection alternative such as this, by making the necessary changes in the region's characteristics only within the GIS, could not be considered.

Implementation of all structural and non-structural flood protection measures discussed above in Section 3.1 would be possible using the floodplain analysis model. However many of them could not be made by changing the region's characteristics in the GIS alone. The addition of many of the previously described measures would require recalibration of the hydraulic model, HEC-2. These measures include the addition of reservoirs, channel modifications, retention ponds, and floodways in the region being considered. Also, existing mitigation alternatives in the region of consideration, could not be eliminated from the GIS images. For example, sections of existing dykes could not be broken in order to flood certain areas for the purpose of protecting others.

Implementation of measures such as these, or any others which would largely alter the volume of water within the region of interest, would require recalibration of the hydraulic model.

3.4.2.2 Potential Alternatives

A wide variety flood of protection alternatives could be generated with the floodplain analysis model by making changes in the GIS database alone. These alternatives involved small but effective changes in the region's characteristics which would not require recalibration of the hydraulic model. Allowable changes included the addition of new small dykes or modification to the elevation of existing ones. Again, modifications such as these could be made in the GIS database alone, provided that they did not cause a change greater than five percent of the overall volume of water in region of interest, as determined by the hydraulic model. Also, specific features having a high risk of incurring heavy damages could be protected by use of measures such as flood-proofing or through their relocation. In addition, non-structural measures such as flood-warning could also be implemented using the GIS.

Though changes to the characteristics of region of interest were to be done primarily within the GIS database only, the HEC-2 model could still be used to assist in the generation of flood protection alternatives. Its main potential ability in this regard was for altering the operations' policies or properties of existing flood mitigation measures. For example, the sizes of existing measures such as conduits, or the operating policies of gates or weirs, used to control water levels, could be altered. Generating alternatives using this form of modification to existing flood protection measures could not be undertaken using the GIS because the information needed to do so was not contained in its database. Changes such as these would not require recalibration of the hydraulic model.

3.4.3 FLOOD SIMULATION ALGORITHM

Using the developed floodplain analysis model, the spatial extent of flood waters associated with specific flood events for the region being considered, could be estimated. In doing so the floodplain analysis model takes into consideration the general topographic characteristics of, as well as all existing flood mitigation measures contained within, the region being modelled. In addition, by changing the region's characteristics, as contained in the floodplain analysis model's input, new potential mitigation alternatives could be generated, and their effects on flooding extent determined. The following is a description of the algorithm used for flood simulation.

The determination of the spatial extent of the flood waters using the GIS was accomplished by using an algorithm developed by Bender and Simonovic (1995). Implementation of this algorithm required the user to separately apply a combination of both GIS commands, and external data transfer programs in connection with the hydraulic model. Input required by the algorithm to describe the region being modelled included the HEC-2 input file as well as the DEMs, and feature and reach images for the GIS component. Water surface elevations were calculated for each reach in the region of interest using the hydraulic model. The calculated elevations were then assigned to their appropriate reaches in the GIS reach image. By subtracting the DEM from the reach image all ground surface areas having a lower elevation than the calculated water surface were identified. However, all areas having a lower elevation than the water surface were not necessarily flooded. This was because the hydraulic model only accounted for potential barriers to water within the reach confines as contained within the HEC-2 input file.

As the reaches had been expanded in the GIS images, additional water barriers described within the DEM had to be considered. In order to determine which locations in the region of interest were flooded, all contiguous submerged areas were identified and given a separate identifier. The individual group of submerged cells corresponding to the location of the main branch of the river, as dictated by the feature image, was selected to represent the spatial extent of the flood waters. An image showing the flooding extent, based on the region's characteristics and implemented flood protection measures, was produced. Using this approach the extent of the flood water was determined by identifying the interface between the calculated water surface and the ground surface as dictated by the DEM. Thus, areas in the region of interest having a lower ground elevation than that of the calculated water surface elevation, which are protected by elevated barriers such as dykes, remain untouched by flood waters. A complete list of the detailed commands and external programs used in this process can be found in Appendix C.

3.4.4 EVALUATION OF ALTERNATIVES

By applying the algorithm described above, flooding can be simulated based on the existing, and generated, flood protection alternatives for the region of consideration. Images showing the flood water extent resulting from each of the different alternatives are produced. Using these images with the feature image for the region of consideration, a set of new images showing areas affected by the flood water can be produced. These new images, produced for each potential flood protection alternative, are referred to in this thesis as flooded feature images. An example of a flooded feature image is shown in Figure 7. This particular image corresponds to the feature image for the Town of Morris shown in Figure 4.

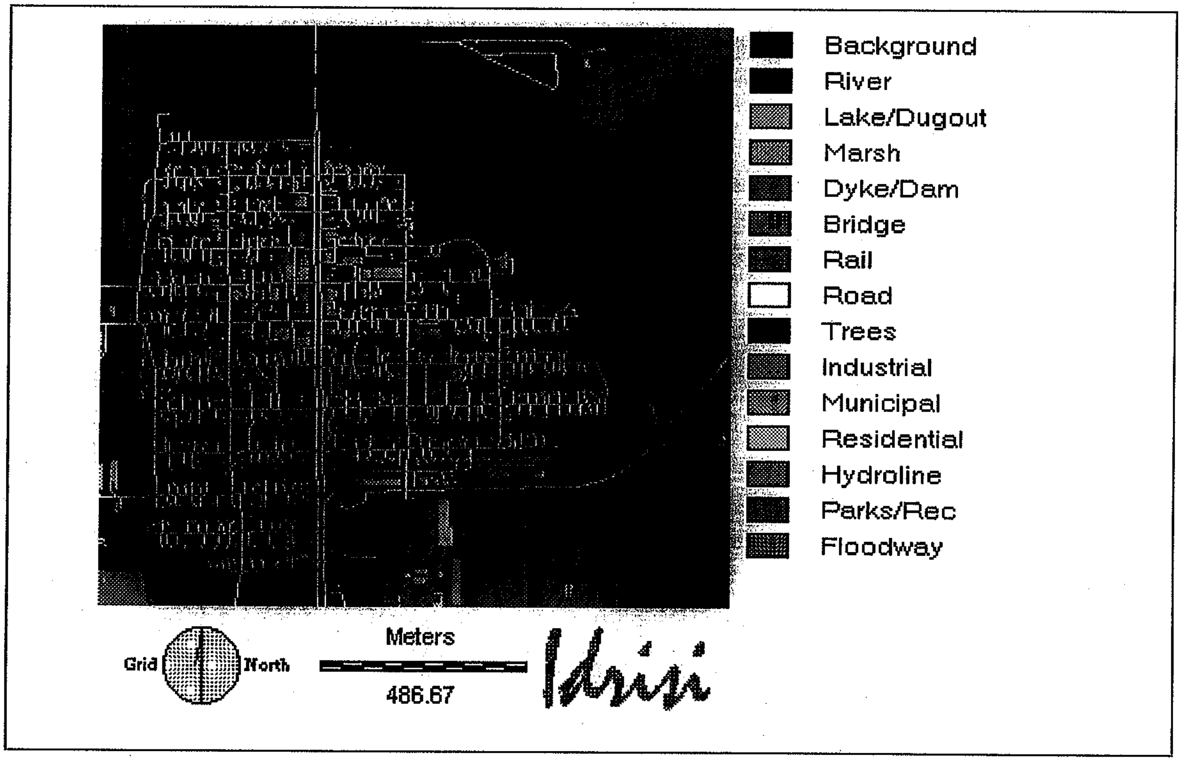

Figure 7: Flooded Feature Image for Town of Morris

Having simulated floods on the basis of existing and new mitigation measures, the impacts resulting from implementation of the various alternatives had to be determined. This could be accomplished using the analytical capabilities of the GIS, and the information contained in the flooded feature images. As can be seen in the sample flooded feature image shown in Figure 7, features affected by flood waters can be identified. The extent of the water shown in this figure corresponds to a selected magnitude of flood event and a particular flood mitigation alternative. Damages to all submerged features in the region of interest, resulting from the implementation of this alternative, can be determined. This is accomplished by relating damages to specific submerged features in the region with characteristics of the flooding event. As discussed above in Section 3.1, these characteristics could for example, include the depth, or velocity of flood waters. By totaling the damages to all features in the region of consideration the impacts corresponding to each of the various flood mitigation alternatives can be determined. Based on the magnitude of these damages, or impacts, each of the flood protection alternatives for the region of consideration can be evaluated. In this research, the costs of implementing the various flood protection alternatives are not considered in their evaluation. By evaluating each of the various simulated flood mitigation alternatives, the one which provides the best level of protection for the region can be determined. The Compromise Programming and Spatial Compromise Programming techniques were selected to assist in evaluating the potential flood protection alternatives. These approaches are described in the following Chapter.

4. DECISION-MAKING USING GIS

Having generated a set of potential flood protection alternatives for the region of consideration, a means of determining the best option from among these alternatives was needed. In order to identify the best alternative, each of the potential alternatives required evaluation. Associated with each of the alternatives are flooding impacts incurred by the region resulting from their implementation. By measuring and comparing these impacts, the best flood protection alternatives may be selected.

As discussed in Section 3.1 there are many different types of impacts produced by flooding events. In evaluating the alternatives, as many of these impacts which can be measured should be considered. The alternatives are evaluated based on the cumulative total of all of the different types of impacts produced by flooding which result from implementation of the potential alternatives. As a result before the alternatives can be compared against one another, the flood impacts associated which each must first be totaled. However, totaling of these impacts often cannot be done through simple addition of their respective magnitudes. This is because while many of the flooding impacts are quantitative in nature and can be represented by a single number, others cannot. For example, impacts such as the elimination of social activities due to evacuation of a community cannot be easily quantified. This type of impact is in fact qualitative in nature, and as a result cannot be easily added or compared to the quantitative impacts such as the dollar value of building damages.

In totaling the impacts produced by flood waters, all damages are often not given equal consideration. For example, the number of hospital routes closed due to flooding would likely be considered more important than the number of bike routes interrupted by flooding. However, the magnitude of the difference in the degree of importance of impacts such as these is often very difficult to quantify. In totaling the impacts, the relative importance of the various damages produced by flood waters must be accounted for. Consequently, totaling and comparing flood water impacts for the purpose of evaluating alternatives is often a very complicated process. This process can be assisted with the use of MCDM techniques.

This Chapter describes the MCDM aspect of the research conducted for this thesis. The Chapter begins with an overview of the role of MCDM techniques and their application in water resources. Included in this is a discussion of a major shortcoming of these techniques. A detailed description of the MCDM technique Compromise Programming is next. The Chapter concludes with a description of a new MCDM technique which was used to facilitate evaluation of the generated potential flood control alternatives. This new approach, which incorporates the use of GIS technology, was developed specifically for application to this research, and is referred to in this thesis as Spatial Compromise Programming.

4.1 OVERVIEW

The field of water resources often requires the use of MCDM techniques. The analysis of flood control alternatives is no exception. The purpose of MCDM techniques is to assist decision makers in identifying the best strategy from a number of potential alternatives or solutions to a particular problem. The need for these techniques arises from the complexity of decision making in the field of water resources. This complexity is produced by many factors. One of these factors includes the necessity to compare qualitative and quantitative criteria. The decision making process is further complicated by the need to consider the relative importance of the various criteria. The difference in importance of the criteria is dependent on the preferences of the decision makers who are evaluating the potential alternatives. Further complexity arises in the consideration of the relative importance of the criteria if multiple decision makers with conflicting interests are involved in the evaluation.

MCDM techniques facilitate decision making and improve the quality of the decisions made by making the decision making process more explicit, rational, and efficient (Hobbs et al., 1992). Using these techniques it is possible to compare alternatives based on both qualitative and quantitative criteria consistently. MCDM techniques also allow application of decision maker's values, or preferences, to the problem in a systematic and unbiased manner. Thus the different degree of importance of the various impacts considered in the evaluation, resulting from the potentially conflicting interests of the decision makers, may also be included in the comparison.

In using MCDM techniques to evaluate a set of potential alternatives, a solution which fully satisfies all criteria often cannot be determined. This is because a single best solution to a particular water resources problem frequently does not exist. This is because of the many different decision makers' interests and opinions pertaining to the relative importance of the criteria, which have to be considered in evaluating the alternatives. Because the different decision makers' interests are incorporated by MCDM techniques, they influence the identification of the best alternative by the techniques. For example, an alternative selected as "best", based on one decision maker's preferences, may not satisfy the interests and values of another. Given different decision maker preferences, the MCDM technique selects a different "best" alternative, from the potential set. As a result MCDM techniques typically are not used to select a single best alternative. They are predominantly used to reduce the set of potential alternatives to a subset of non-inferior solutions which are worthy of further consideration (Simonovic, 1995). The subset of non-inferior solutions determined by MCDM techniques are referred to as non-dominated solutions. For each solution which is excluded from the non-dominated subset, there exists a non-dominated solution within the subset which better satisfies at least one criteria without reducing the level of satisfaction of the other criteria being considered. Examples of past applications of MCDM techniques to water resources problems are described in the following paragraphs.

In Simonovic 1989 the Compromise Programming technique was used for the purpose of evaluating alternative solutions for the development of a water resources master plan. Evaluation of the alternatives was based on their ability to satisfy demand for municipal water supply, industrial water supply, irrigation, hydropower generation, flood protection, and water quality control using available water supplies. In this case the Compromise Programming technique was used to identify the most robust solution.

Shafike et al. (1992) used the Compromise Programming, ELECTRE II, and MCQA II MCDM techniques to analyze a groundwater contamination management problem. Specifically the techniques were used to rank different management programs in order to identify a "satisficing" alternative. Evaluation of the alternatives was based on the ability of the different management programs to: a) maximize the fresh water supply volume; b) minimize the cost of containment, restoration and pumping for water supply; and c) minimize the local drawdown effects at the contaminated location of the aquifer in order to promote conservation.

Gershon et al. (1982) applied MCDM techniques to water resource problems involving qualitative criteria. Specifically the ELECTRE I and II methods were used to evaluate the impact of alternate river basin development strategies. Evaluation of the various alternatives in this case was based on their impacts on the river basin pertaining to water supply, flood protection, environmental protection, level of utilization, and recreation. ELECTRE I was used first to reduce the set of possible alternatives to a subset of realistic solutions. ELECTRE II is then applied to order, or rank, the alternatives in the subset.

The criteria values associated with the alternatives, which are used by MCDM techniques to evaluate the alternatives, are often spatially variable. With reference to the criteria used in the above examples, water demands and supplies for such purposes as municipal water supply, industrial water supply, irrigation, hydropower generation, water quality control, and recreational use are frequently unevenly distributed across the region in which they occur. With respect to flood control, the impacts produced by flooding are typically not the same for all geographic locations within the region of interest. The distribution of the flood impacts across the region are dependent on the implemented flood protection measures. For example, implementation of a particular mitigation measure may reduce flood water impacts in one area, while providing no added protection for another. It is also possible that by protecting one area through addition of a flood protection measure, flooding in other areas may increase. As a result the alternative causing the greatest reduction of flood impacts for one area may not be the best solution for all locations in the region of interest.

Conventional MCDM techniques unfortunately do not consider the spatial variability of the criteria values which are used to evaluate potential alternatives. The criteria values which they use represent average or total impacts incurred across the entire region being considered. Thus in identifying the best solution from a set of potential flood mitigation alternatives using conventional MCDM techniques, only the region as a whole is considered. By doing so the localized, and potentially negative, impacts resulting from implementation of the various flood protection alternatives are ignored. Consequently, the alternative identified as best for an entire region by a conventional MCDM may not be the best for all locations within that region.

4.2 COMPROMISE PROGRAMMING

Compromise Programming is a MCDM technique which can be used to identify the best solution from a number of potential alternatives (Zeleny, 1973). The alternative selected as the "best" by this technique is that one which is closest to the ideal solution. The "ideal solution" is that point which provides the extreme value for each of the criteria considered in the analysis. The distance from the ideal solution for each alternative is measured by what is referred to as the distance metric. This value, which is calculated for each alternative, is a function of the criteria values themselves, the relative importance of the various criteria to the decision makers, and the importance of the maximum deviation from the ideal solution (Simonovic, 1989). All alternatives are ranked according to their respective distance metric values. The alternative with the smallest metric, or least distance from the ideal solution, is typically selected as the "best solution". Shown in Equation (1) is the formula used to compute the distance metric values (L_j) for a set of n criteria and m alternatives.

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

where: L_j is the distance metric;
f^*_i is the optimal value of the i^{th} criteria;
$f_{i,w}$ is the worst value of the i^{th} criteria
$f_{i,j}$ is the value of the i^{th} criteria for alternative j
w_i are weights indicating decision maker preferences
p is a parameter ($1 \le p \le \infty$)
i=1,n criteria
j=1,m alternatives

A decision maker may influence the calculated value of the distance metric through the selection of two distinct types of weights, shown in the above equation. The first set of weights (w_i) describes the decision makers' relative preferences toward each of the various criteria used in evaluating the alternatives. The second weight (p) is a single value which emphasizes the importance of the maximum deviation of all calculated distance metric values from the ideal solution. This weight requires brief discussion. As stated above its range of values may vary from one to infinity. Given a weight p=1, all deviations of the criteria from their ideal value, in the calculation of the distance metric, are treated equally. A greater concern for the maximum deviation by decision makers may be expressed by selecting a larger value of p. For the value of $p=\infty$, the min-max criterion is achieved (Simonovic, 1989).

As discussed in Section 4.1 a single best alternative which satisfies all criteria cannot be determined using MCDM techniques. MCDM techniques are typically used to select a set of "best" alternatives from the potential options. This set is referred to as the non-dominated set. Generation of the non-dominated set of alternatives is accomplished using the Compromise Programming technique by solving Equation (1) for all values of the weight p. As the range of the weight p is infinite, further reduction of the set is necessary for practical application. Typically the compromise set is approximated by solving Equation (1) using values of $p=1$, 2 and ∞. The alternatives which are closest to the ideal solution are identified in the approximation to the compromise set of solutions.

The criteria used in above equation express impacts produced by, or characteristics associated with each of the alternatives. Criteria may be qualitative or quantitative in nature and can represent both positive and negative implications with respect to the decision makers' preferences. Often the criteria values associated with the alternatives are spatially variable. However as shown in Equation (1) no consideration is given to this. Therefore in identifying the best solution using Compromise Programming only the region as a whole is considered. As a result, local impacts associated with or produced by the alternatives are ignored. Thus the alternative selected as best by the approach may not be the best solution for all locations in the region of interest. This is a major shortcoming of Compromise Programming and many other conventional MCDM techniques. The potential for the presence of spatial variability in the criteria values and the implications of not considering them are shown in the following example. In order to be consistent with the case study discussed in Chapter 5, this example will also be based on decision making pertaining to flood control issues. In this demonstration the hypothetical region of interest is described by Figure 8.

Farm	Farm	Farm
Park	Town	Town
Park	Town	Town

Figure 8: Sample Region of Interest

This area consists of a mixed variety of land use types in close proximity to a river. The region has been divided into a grid as shown in Figure 8 to help illustrate the spatial variability of the criteria values. To alleviate damage produced by flooding in this region, three potential mitigation alternatives are proposed. All of these alternatives consist of dyking strategies. In each alternative one of the respective land use types is completely surrounded by dykes. The alternatives are evaluated on the basis of two criteria: a) flood water depth; and b) flood water velocity. Given a flood of arbitrary magnitude the flood water depths and velocities for each alternative and land use type are shown in Figures 9 and 10 respectively.

Alternative 1

2.4	2.5	2.3
2.0	0	0
1.8	0	0

Alternative 2

2.4	2.5	2.3
0	1.7	1.9
0	1.5	1.5

Alternative 3

0	0	0
2.0	1.7	1.9
1.8	1.5	1.5

Figure 9: Sample Flood Water Depths

Alternative 1

1.8	1.9	1.7
1.5	0	0
1.4	0	0

Alternative 2

1.8	1.9	1.7
0	1.3	1.4
0	1.1	1.1

Alternative 3

0	0	0
1.5	1.3	1.4
1.4	1.1	1.1

Figure 10: Sample Flood Water Velocities

Selection of the best alternative for this example is based on minimizing the flood water depth and velocity. Using a MCDM technique (though not necessary due to the problem's simplicity) such as the Compromise Programming technique the criteria values for each alternative would first be averaged across the region of interest. The average flooded depths for alternatives one, two and three, are 1.22, 1.53 and 1.16 units respectively. The average flood water velocities for alternatives one, two and three, are 0.92, 1.14 and 0.87 units respectively. To determine the best alternative using Compromise Programming, calculation of a distance metric for each alternative is normally necessary. However, because of this sample problem's simplicity, consideration for decision makers preferences, and calculation of the distance metrics are not required. Without any computations it is obvious that alternative three, having the least average flood water depth and velocity, would be considered the best flood mitigation strategy by the Compromise Programming technique for the region of interest.

In reviewing the criteria values shown in Figures 9 and 10 it is apparent that the flood water impacts, resulting from implementation of each of the three alternatives, are not evenly distributed across the region of interest. Thus selection of alternative three does not necessarily provide all areas in the region with the same level of benefit. In fact, implementation of this alternative, as shown by the criteria values, provides only the farmland with any benefit. Unfortunately these localized impacts are not considered in the selection of the best alternative when using conventional MCDM techniques. In order to address this shortcoming in conventional MCDM techniques the Spatial Compromise Programming technique was developed in this research.

4.3 SPATIAL COMPROMISE PROGRAMMING

GIS can be used to include spatial considerations in MCDM. Past applications of GIS in decision making have predominantly involved the determination of the best spatial location for alternatives based on sets of predetermined criteria. The research presented in this thesis takes the reverse approach by determining the best alternative for each spatial location based on decision maker preferences and criteria. The objective in doing so was to account for potential spatial variation in the criteria values. To accomplish this task, a new MCDM technique was developed by embedding the Compromise Programming technique within a GIS framework. All aspects of the Compromise Programming technique are represented within the GIS. Variables necessary for Compromise Programming are described using GIS raster images. All required calculations are performed by the GIS by applying GIS commands to the variables described in the raster images. This new technique, which is described below, is referred to herein as Spatial Compromise Programming.

The Spatial Compromise Programming technique identifies the best solution from a number of potential alternatives for each location within the region of interest. As was the case in Compromise Programming, with Spatial Compromise Programming distance metrics are the basis on which alternatives are evaluated. However with the new approach, rather than determining a single value per alternative, a distance metric is calculated for each impacted location, for each alternative. The region of interest encompasses all geographic locations which are impacted by the combined group of alternatives. In this approach the region is represented by a raster feature image of the study area. In this way each location within the region of interest, for which a distance metric is calculated, is represented by an individual raster cell within the feature image.

The criteria values for the alternatives and decision maker preferences are needed for computation of the distance metrics. Criteria values associated with each of the alternatives are contained within sets of criteria images which are georeferenced with the feature image mentioned above. Alternatives have their own individual set of images in which each separate image represents a single criteria. Therefore, the total number of criteria images equals the product of the number of criteria and the number of alternatives. Each raster cell in a criteria image contains the criteria value for that geographic location associated with a particular alternative. If the criteria value is spatially variable then each affected cell, or location, within the image has a different value. If the alternative impacts all locations within the region of interest equally, all impacted cells contain the same criteria value. Thus using GIS the spatial distribution of the criteria values are captured.

The optimal and worst criteria values were also required for computation of the distance metrics. Once again, rather than having just a single value for each criteria, the best and worst criteria values are determined for each location, or raster cell, in the feature image. Thus each criteria has a best and worst value image. The criteria values contained in the images, to be used for computation of the distance metrics, may be the actual or absolute minimum and maximum. Choice of this is dependent on the criteria themselves and the opinion of the decision makers. If it is the actual extreme values that are desired, these may be determined by comparing the values of the individual criteria for each location, between the alternatives. The best and worst value for each location can be extracted and placed into separate images using GIS commands. By using actual values, if the criteria values are spatially variable so too will be the optimal and worst criteria value images. If the absolute maximum and minimum criteria values are required, new images georeferenced to the feature image are produced, whose initial value is that of the best or worst criteria value. Having a constant value, absolute optimal and worst criteria value images are not spatially variable.

Based on the criteria images discussed above, and the decision maker's preferences, a distance metric image is produced for each alternative. Contained in the distance metric images are distance metric values for each impacted raster cell in the region of interest. The 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. This process is illustrated in Figure 11. All necessary computations are performed using GIS commands. Locations, or raster cells, in the study area for which there is no criteria value, or in other words, no impacts, are assigned a distance metric value of zero.

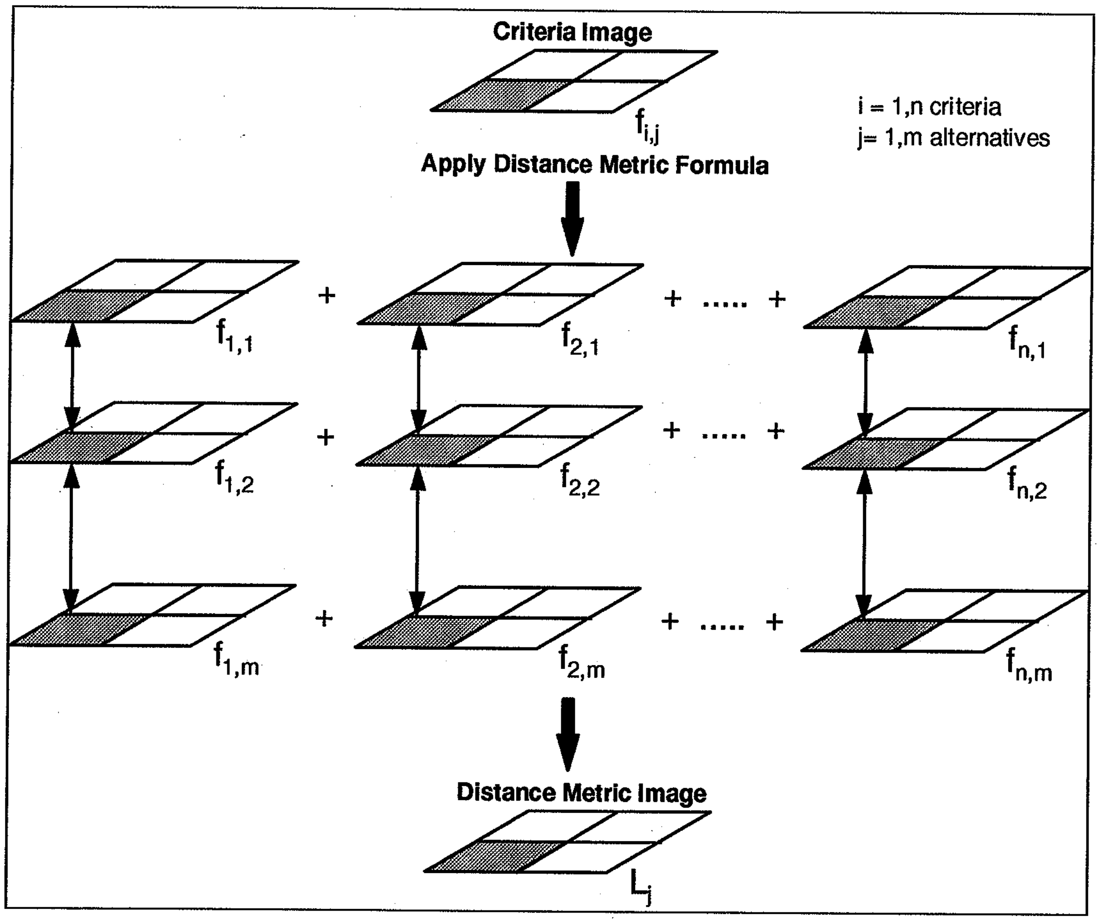

Figure 11: Cell by Cell Calculation of Distance Metric Values

In the Spatial Compromise Programming technique the best alternative for each location is determined by comparing the values in the distance metric images for each individual raster cell between the alternatives. As stated above, in Compromise Programming the alternative with the smallest distance metric is typically selected as best. However, identification of the alternative with the smallest distance metric based on a cell by cell comparison between the distance metric images is not possible within the GIS. This is due to the limited analytical capabilities of the selected GIS software. However identification of the alternative with the largest distance metric for each location is feasible. Based on the classical distance metric formula presented in Equation (1) this would translate into determining the worst alternative for each location. As a result it was necessary to rewrite the distance metric formula in such a way that the better the alternative, the larger the distance metric value. The conventional distance metric formula measures the distance of each alternative from the ideal solution. The smaller the distance the better the alternative. For the Spatial Compromise Programming technique this formula was rewritten to determine the distance of each alternative from the worst solution. Thus the alternative with the largest distance metric value would be the best. If the values contained within the distance metric images were calculated based on this logic the GIS could be used to identify the best alternative for each location. The modified distance metric formula for the Spatial Compromise Programming approach is shown in Equation (2). Equation (2) was developed in a manner such that when applied it would produce the same ranking of alternatives as the classical distance metric formula shown in Equation (1).

$$L_j = \left[\sum_{i=1}^{n} w_i^p \left| \frac{f_{i,w} - f_{i,j}}{f_i^* - f_{i,w}} \right|^{1/p} \right]^p \qquad (2)$$

where: L_j is the distance metric
f_i is the optimal value of the i^{th} criteria
$f_{i,w}$ is the worst value of the i^{th} criteria
$f_{i,j}$ is the value of the i^{th} criteria for alternative j
w_i are weights indicating decision maker preferences
p is a parameter ($1 \le p \le \infty$)
i=1,n criteria
j=1,m alternatives

Using the values in the distance metric images the best alternative is determined for each location. The distance metric values for each location in the region of interest, as described by the feature image, are compared between the alternatives. The alternative having the largest distance metric value for each raster cell is selected as the best. This cell by cell comparison between the alternatives is undertaken for each location in the region of interest. This process is illustrated in mathematical form by Equation (3). Based on this comparison, an image identifying the best alternative for each location is produced. Each cell within this image contains a number corresponding to the alternative which is best for that particular geographic location. By inspecting this image, decision makers are able to identify the alternative providing the greatest benefit for each location contained in the feature image.

$$\max\left\{ L_{j,x,y} = \left[\sum_{i=1}^{n} w_i^p \left| \frac{f_{i,w,x,y} - f_{i,j,x,y}}{f^*_{i,x,y} - f_{i,w,x,y}} \right|^{1/p} \right]^p \right\} \tag{3}$$

where: $L_{j,x,y}$ is the distance metric
$f^*_{i,x,y}$ is the optimal value of the i^{th} criteria
$f_{i,w,x,y}$ is the worst value of the i^{th} criteria
$f_{i,j,x,y}$ is the value of the i^{th} criteria for alternative j
w_i are weights indicating decision maker preferences
p is a parameter ($1 \leq p \leq \infty$)
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
b is the number of columns in the image

Returning to the example discussed in Section 4.1, the Spatial Compromise Programming technique could be used to provide decision makers with a more detailed evaluation of the three potential alternatives. Required as input for this MCDM technique are raster images describing the topography of the study area as well as the extents and magnitudes of the potential impacts which would be produced by each alternative. Figure 8, which shows the land use types in a grid like fashion, represents the raster feature image describing the region of interest. The three sets of flood water depths and velocities shown in Figures 9 and 10 represent the criteria images for each of the alternatives. Again due to the simplicity of this problem it is not necessary to consider the decision makers' preferences, or to calculate distance metrics for each alternative and location. Through visual inspection of the criteria images, the outcome produced by implementation of the Spatial Compromise Programming technique can be determined intuitively. Shown in Figure 12 is the final best alternative image produced by evaluating the three flood protection measures using the Spatial Compromise Programming technique.

3	3	3
2	1	1
2	1	1

Figure 12: Sample Best Alternative Image

Contained in each cell of the image are the numbers corresponding to the best alternative for each location in the region of interest. Thus the Spatial Compromise Programming technique can be used to show that alternative three, as determined to be the best alternative by conventional Compromise Programming, is not necessarily the best solution for each location in the region of interest.

As shown in the example, criteria values associated with the set of potential flood protection alternatives, are often spatially variable. These criteria values are the basis for evaluating the alternatives using MCDM techniques. Conventional MCDM techniques however do not have the ability to take the spatial variation of the criteria values into consideration. Conventional MCDM techniques typically use criteria values which represent either the average or total impacts incurred by the entire region of interest. Thus in the selection of the best solution from a set of potential alternatives only the region as a whole is considered. Localized impacts produced by each alternative are ignored. As a result the alternative selected as best for the region of interest as a whole may not be the best solution for each location in the region. This shortcoming of conventional MCDM techniques is demonstrated in the example described in this Chapter.

By using GIS technology the spatial variability of the criteria values is taken into consideration. By maintaining the spatial variability of the criteria values, the occurrence of localized impacts produced by, or associated with, each alternative can be detected. Also identified are the specific locations where these localized impacts are incurred. Applying the Spatial Compromise Programming technique, using the spatially variable criteria values, the best alternative for each location in the region of interest can be determined. In this way decision makers are provided with useful information regarding the implications of selecting and implementing particular alternatives. Specific locations incurring both positive and negative impacts due to the implementation of particular alternatives are identified. Knowledge of this information could assist decision makers in their selection of the best solution from a set of potential alternatives.

5. CASE STUDY: FLOODPLAIN ANALYSIS OF THE RED RIVER VALLEY

5.1 BACKGROUND

A Floodplain analysis of the Red River Valley, was selected to demonstrate the capabilities of the Spatial Compromise Programming technique. This area is located in the south-central potion of the province of Manitoba, Canada. It consists of low-lying flat prairies predominantly used for agricultural purposes. The main population center in this area is the City of Winnipeg which is located in the downstream portion of the valley, at the confluence of the Red and the Assiniboine Rivers. Other communities of significant size further upstream in the Red River Valley include the towns of St. Adolphe, Morris, and Emerson.

The Red River Valley is very prone to flooding and has historically (1826, 1950, 1979, 1996) incurred extensive damages to both urban and agricultural areas from flood waters. The major floods are typically seasonal in nature, and are the result of combined spring snowmelt and rainfall runoff along both the Red and Assiniboine Rivers (Krenz and Leitch, 1993). The largest recorded historic flooding event for this region occurred in 1826. More than 900 square miles of land were inundated in this flood. The 1950 flooding event, referred to as the "Winnipeg flood", was one of the largest natural disasters in Canadian history (Rannie, 1980). Water levels in the Red River rose 30.3 feet above datum within the City of Winnipeg (Bumsted, 1993). In this flood roughly 640 square miles of cropland were submerged, approximately 10 500 homes were flooded, and 100 000 people had to be evacuated. Roughly 30 million dollars was paid out in flood damages (United States Geological Survey, 1952). However the true cost of the flood may have exceeded 100 million dollars. During this flood, communities located upstream of the City of Winnipeg were completely submerged. Also significant portions of the City of Winnipeg were extensively flooded. Shown in Figure 13 is a sample of the extents of the 1950 flood within the City of Winnipeg.

Figure 1: University of Manitoba during the 1950 Flood

5.1.1 EXISTING FLOOD PROTECTION

To alleviate the damages produced by flooding in the Red River Valley a number of structural and non-structural flood protection measures were implemented. Some of these measures (Figure 14) include: a) a dyking system along both the Red and Assiniboine Rivers; b) flood pumping stations within the City of Winnipeg; c) Shellmouth Reservoir; d) Portage Diversion; and e) Red River Floodway. A brief description of these measures follows.

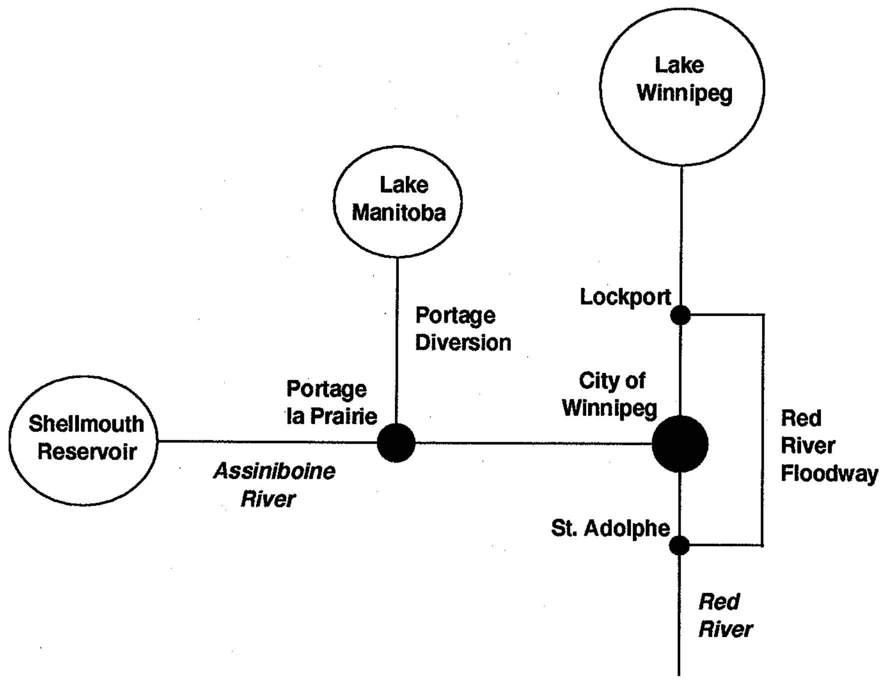

Figure 14: Flood Control System for the City of Winnipeg and Surrounding Area

5.1.1.1 Dykes

Because of the extremely flat floodplain, some level of protection for the areas surrounding both the Red and the Assiniboine River, was required. Consequently dykes were constructed to protect the City of Winnipeg and surrounding communities. Though dyking is an effective mitigation strategy, due to the high costs of building dykes, it was not cost effective to dyke the entire banks of the two rivers. Thus dykes were constructed strategically in order to provide protection to those areas with a high risk of incurring heavy damages. In the City of Winnipeg features such as roads and railway beds in close proximity to the two rivers were built to high elevations in order to serve as a barrier to flood waters. Outside of the City the eight largest communities along the Red River, which include Emerson, Letellier, Dominion City, St. Jean Baptiste, Morris, Rosenort, Brunkild, and St. Adolphe were surrounded by ring dykes composed of both earthen material and sheet piling. All dykes were constructed such that they would be broad enough to permit the addition of smaller temporary dykes in the event of a larger flood. The protection level provided by the dykes is equal to the water elevation which occurred during the 1950 flood (Rannie, 1980).

5.1.1.2 Flood Pumping Stations

Within the City of Winnipeg there are 34 flood pumping stations located along both the Red and Assiniboine Rivers. The purpose of these stations is to accommodate the release of in-city storm water. Throughout the city the storm and combined sewers are set to overflow into the rivers in case of internal flooding. However, because the flow within the sewers is governed by gravity, if the river stage is higher than the sewer outlet, backing up can occur. To prevent backup, gates were installed on the sewer outlets. In the event that gravimetric flow within the sewers cannot occur, the flood pumps will expel the water over the dykes.

5.1.1.3 Shellmouth Reservoir

The Shellmouth Reservoir is a flood mitigation project located near Russell, Manitoba. It was built to control the Assiniboine River and its tributaries which flood once per decade on average. Completed in 1969, the project utilizes a natural valley with the addition of a 70' high 4200' long downstream dam face built at the junctions of the Shell and Assiniboine Rivers. The reservoir itself is 35 miles long, with a total storage capacity of 390 000 acre-ft of which 225 000 is allocated for the storage of flood waters. In this area flooding, which is mainly caused by heavy spring runoff, results in extensive damage to residential, agricultural, and industrial property along the river. Downstream communities are frequently flooded, and the increased water level also contributes to the damages inflicted in Winnipeg. The reservoir has the capability of storing the excess spring flood-water, and distributing it throughout the course of the summer to ensure an adequate base flow for the rivers.

5.1.1.4 Portage Diversion

The Portage Diversion, completed in 1970, was constructed to alleviate flooding of the Assiniboine River specifically between Portage la Prairie and Winnipeg. In this section of heavy agricultural production the land slopes away from the river. In times of flooding this makes drainage of the area difficult. To avoid this difficulty attempts have been made to prevent overtopping of the banks. When flood conditions exist downstream of Portage la Prairie or at

Winnipeg, the Portage Diversion is used to divert water from the Assiniboine River to Lake Manitoba. At present the maximum discharge capacity is 25 000 cfs.

5.1.1.5 Red River Floodway

The Red River Floodway, Manitoba's largest flood protection project, was completed in 1968. The floodway is a 30 mile long channel, with a flow capacity of 60 000 cfs, which diverts floodwaters around the east side of the City of Winnipeg and then reconnects with the Red River near the town of Lockport. The entrance to the floodway is on the south side of the City, near the community of St. Adolphe. The flow of water within the Red River is unaffected by the floodway until the discharge reaches 30 000 cfs. At this flow the water surface reaches sufficient elevation to permit flow into the floodway. The flow of water into the floodway channel is controlled by a gate structure located downstream of the floodway entrance. The gates, which are normally flush with the bottom of the river, can be raised to produce a backwater effect which forces water into the floodway channel. Water is prevented from passing around the control structure and floodway inlet, into the City, by dykes which extend 27 miles on either side of the river and floodway entrance. The higher the gates are raised, the greater the backwater and thus the more water is forced into the floodway. By producing a backwater with the gates, the water levels at the upstream communities are increased. The operations policy of the floodway is designed such that under normal conditions the backwater does not alter the upstream water levels in comparison to their natural levels before construction of the floodway. However, in the case of a declared state of emergency, in order to save the downstream City of Winnipeg, flooding of the upstream communities is required (Manitoba Department of Natural Resources, 1984).

5.1.2 NECESSITY FOR RE-EVALUATION OF EXISTING MITIGATION STRATEGY

It is estimated that the combined measures described in Section 5.1.1 can provide protection for the City of Winnipeg from river flows up to 169 000 cfs. This magnitude of flooding event corresponds to a predicted return period of approximately 165 years (Rannie, 1980). Though this level of flood protection is quite high, the overall flood mitigation strategy for this area requires improvement. Because the described measures were developed separately over time, at present they are operated somewhat independently. The level of coordination that does exist was developed at the time of creation of the measures, and requires updating. Also, measures such as the Shellmouth reservoir were developed for other purposes in addition to providing flood protection. As a result, the flood protection objective is often compromised in order to meet other conflicting demands for reservoir storage. Thus the optimal efficiency of the existing flood mitigation projects is not currently being attained.

Another major flood control issue in this area that requires attention is the distribution of benefits from the various measures. In order to protect certain areas in this region, others are frequently sacrificed. This decision is typically based on the economic values of the different areas, and the potential that they will incur damage. This tradeoff has led to bitter conflicts between different areas within the region. The biggest conflict is between the City of Winnipeg and the communities located upstream on the Red River. The focus of this conflict is typically centered on how the Red River Floodway is operated. Based on the operating procedures described above, occupants of upstream communities feel that they are needlessly sacrificed in order to protect downstream areas within the City. In addition to this, the accuracy of the "natural" upstream water levels which are required to be maintained through normal operation of the floodway are often questioned. Thus, there is a need for further re-evaluation of the current overall flood mitigation strategy for City of Winnipeg and surrounding area.

The floodplain analysis of the Red River Valley was selected as a case study in order to demonstrate the benefits of the developed MCDM technique for addressing the conflict between upstream and downstream communities. The study focus is a 7.5 by 5 km region encompassing the community of St. Adolphe along the Red River. As St. Adolphe is the closest community upstream from the floodway inlet and gate structure, it is the one which is most heavily influenced by the floodway operation. Given normal operation of the floodway, the backwater that it produces extends many kilometers upstream beyond St. Adolphe. As a result its operation is frequently responsible for heavy damages to the community and surrounding areas. For this reason, the largest conflict of the region is between St. Adolphe and City of Winnipeg. Thus is the main reason for selecting this area for the case study.

The objective of the floodplain analysis was to identify the best flood protection strategy, from a set of potential alternatives for the case study area. First a number of flood protection alternatives for the St. Adolphe region were generated. Using the floodplain analysis model, developed as part of this research and described in Chapter 3, the flood water extent corresponding to each alternative was determined. Impacts produced by flood waters resulting from implementation of the various alternatives were identified and estimated using the floodplain analysis model. Each of the potential alternatives were evaluated based on the estimated impacts. The objective in the evaluation was to identify the alternative which minimizes the impacts produced by flood waters in the St. Adolphe region.

Three different types of flood water impacts were used as criteria to evaluate the alternatives. The interests of the different groups of people affected by the flooding in the region (i.e., upstream and downstream) were also taken into account. Due to these multiple considerations, evaluation of the potential flood control alternatives was a complex process. Consequently, the evaluation process required assistance from a MCDM technique. Both the Compromise Programming and Spatial Compromise Programming techniques were used to evaluate the alternatives.

The Compromise Programming technique was used to identify the best flood protection alternative for the region as a whole. This was done by considering the flood water impacts as incurred by the entire region. Using the Spatial Compromise Programming technique the best alternative was determined for each location in the St. Adolphe region. This was done by considering the localized impacts produced by flooding, that were associated with the implementation of the various potential flood protection alternatives. By identifying the best alternative for each geographic location, potential sources of conflict between upstream and downstream communities which would stem from implementation of the various alternatives are made apparent. The case study concludes with a comparison of the alternative evaluations produced by the two different MCDM techniques.

5.2 FORMULATION OF FLOOD CONTROL ALTERNATIVES

The first step in the case study analysis was to prepare input for the floodplain analysis model. This input included a description of the characteristics of, and flood mitigation measures implemented in, the case study region. This information was contained in two different sources of input to the floodplain analysis model: the HEC-2 hydraulic model input file; and the GIS images. The HEC-2 input file, which had been calibrated to the historic 1979 flooding event for the St. Adolphe region by the Manitoba Department of Natural Resources was used in the case study analysis. A feature image and DEM were required as input by the GIS component of the floodplain analysis model. All necessary steps were taken, as discussed in Appendix A, to prepare a raster feature image and DEM for the floodplain analysis model. Shown in Figure 15 is a sample of the raster feature image describing the St. Adolphe region.

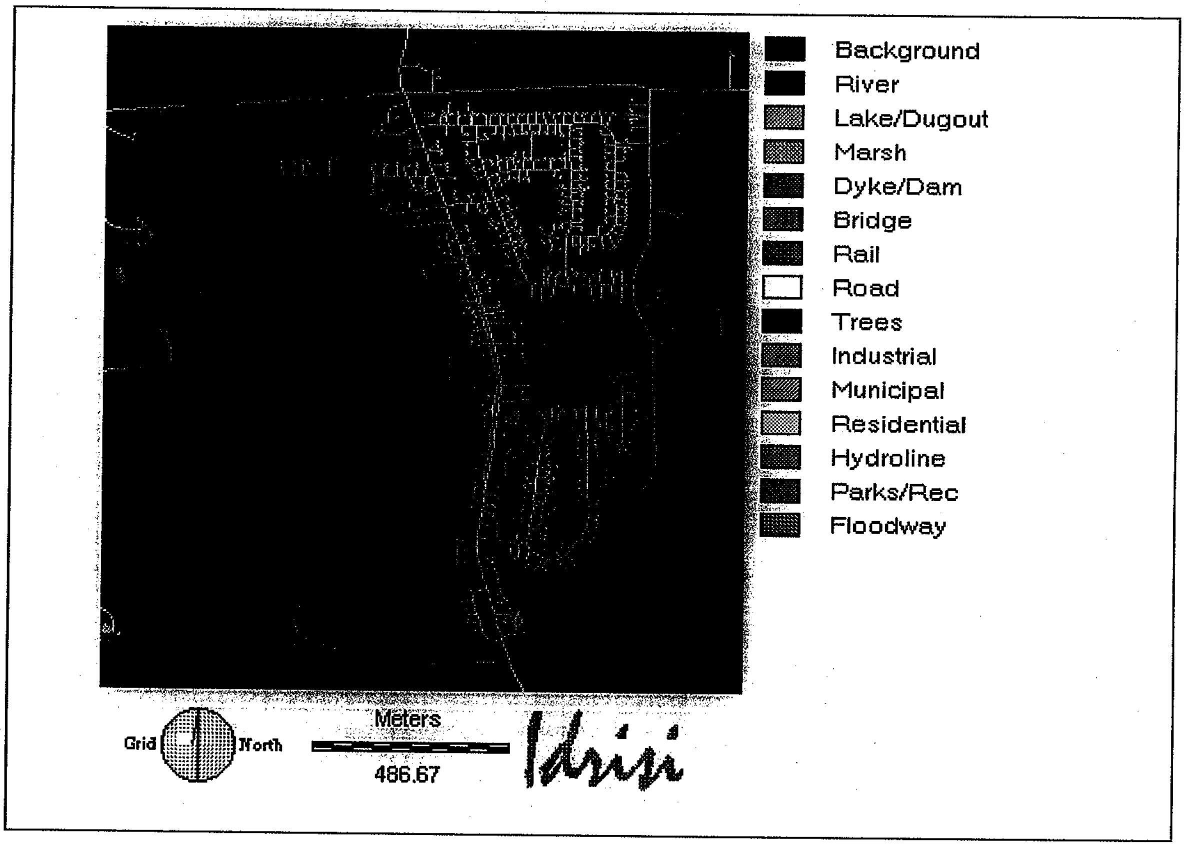

Figure 15: Sample of feature image describing the St. Adolphe region

Based on existing characteristics of the study area the floodplain analysis model was used to determine the flooding extent in the St. Adolphe region. By changing the characteristics of the region, as contained in the floodplain analysis model's input files, new flood protection alternatives were generated. In the case study four potential flood protection alternatives were generated for the town of St. Adolphe and surrounding area. The alternatives consisted of a combination of new and modified existing structural and non-structural mitigation measures. Specifically these measures included the implementation of various combinations of the following measures: a) construction of small ring dykes around specific areas; b) alteration of operation policy for Red River Floodway; c) flood proofing of features having high risk of incurring heavy damages from flood waters; and d) flood warning for the community of St. Adolphe and surrounding areas.

A description of the different combinations of previously introduced measures used in each of the four alternatives for the case study follows. The changes in the floodplain analysis model input, necessary for implementation of the alternatives are then described.

5.2.1 GENERATED ALTERNATIVES

5.2.1.1 Base Case Alternative

The first alternative represented the existing characteristics of, and the flood protection measures which have already been implemented in, the town of St. Adolphe and surrounding area. As this community experiences flooding frequently, knowledge of an impending floodwave can be used to significantly reduce the damages produced by flood waters. For this base alternative, flood warning was provided to the community and surrounding areas. In order to protect the City of Winnipeg, the Red River Floodway was operated under normal conditions for this first flood simulation. Based on the floodway's operations policy, the backwater produced by the gates would raise water levels in the town of St. Adolphe and the surrounding areas to their "natural" levels.

5.2.1.2 Protection of Upstream Communities

In order to better protect the upstream communities the second alternative called for a decrease in the height of the floodway gates, in comparison to normal operation. The gates were lowered to a level such that the water surface elevation at the floodway entrance was decreased by 0.30 m. Also, in this alternative all buildings in the study region were flood proofed to a height of 1 m above the natural ground elevation. Thus, if a building had a depth of submergence which was less than 1 m it was considered to be unharmed. If the flood water overtopped the barrier, damage to the structure was incurred as if there was no barrier at all. Finally, in contrast to the first alternative, no flood warning was given to the communities.

5.2.1.3 Protection of the City of Winnipeg

In the third alternative selected for the case study, floodway operation was altered to provide better protection for the City of Winnipeg. The height of the floodway gates was changed such that the water surface elevation at the floodway entrance was increased to 0.30 m above the normal level. In providing a better level of protection to the City this alternative caused an increase in upstream flooding. To combat the increased upstream water levels once again all buildings in the region of interest were flood proofed to an elevation of 1 m. To further reduce the impacts caused by the flood waters, in this alternative the communities were given warning of the impending flood.

5.2.1.4 Protection of St. Adolphe

Finally, the fourth alternative called for protection of the town of St. Adolphe as a high priority. The entire town was surrounded by a dyke with an elevation significantly greater than that of the existing topography. For this alternative the floodway was operated normally, producing the same water surface elevations in the reaches as in the first alternative. The addition of the ring dyke for this alternative altered the overall volume of water in region as determined by hydraulic model. However, because the community of St. Adolphe is very small, the volume of water which was displaced by the dyke was also small. This alteration was deemed acceptable because it was insignificant enough to produce drastic implications in downstream areas. Also, in this alternative all areas within the study region were not provided with flood warning.

5.2.2 IMPLEMENTATION OF FLOOD CONTROL ALTERNATIVES

The alternatives were created within the floodplain analysis model by altering the characteristics of the region as represented in both the HEC-2 input file and GIS images. Specifically, for purposes of constructing ring dykes, the elevation of the terrain as represented in the DEM was changed to the height desired for the dykes. To alter the operation of the floodway, the HEC-2 input file had to be modified. In the input file, the downstream starting water surface elevation was changed, based on simulated alteration in control of the floodway gate structure. Implementation of the floodproofing measure did not require a change in either the GIS or hydraulic model database. This was because this measure did not alter the region's terrain or the operation of any existing mitigation measures. Also, as flood warning is a non-structural measure, it did not require any physical changes in region's characteristics either. Both flood proofing and flood warning are measures which cause a direct reduction in impacts to specific features, as opposed to affecting the spatial extent of the flood waters as the other measures do. Consequently, the effects of these two measures were accounted for in the calculation of flood water impacts as determined by the floodplain analysis model.

Given the new potential flood mitigation alternatives for the region, as reflected by changes in the hydraulic model and GIS databases, the floodplain analysis model was used to simulate the effects of their implementation. The first task of the model was to calculate water surface elevations for the St. Adolphe region. Because the hydraulic model was calibrated to the 1979 flooding event, all alternatives were tested against this flood magnitude. This historic flood event resulted in a water elevation of 233.3 m above sea level, at the floodway entrance. Backwaters were calculated using the hydraulic model with this elevation as reference. As dictated by the calibrated HEC-2 input file the region was sub-divided into six distinct reaches. The reaches were numbered from north to south starting from that part of the region furthest downstream. The water surface elevations for each reach, shown in Table 2, were determined based on the different operating policies governing control of the floodway gates.

Table 2: Water Surface Elevations Produced by each Alternative

Reach #	Water Surface Elevations (m)			
	Alternative 1	Alternative 2	Alternative 3	Alternative 4
1	234.2	234.1	234.3	234.2
2	234.3	234.2	234.4	234.3
3	234.4	234.3	234.5	234.4
4	234.5	234.4	234.6	234.5
5	234.6	234.5	234.7	234.6
6	234.7	234.6	234.8	234.7

Water surface elevations for each reach were determined using the hydraulic model component of the floodplain analysis model and then were transferred to the GIS in the form of a reach image. Using the GIS's analysis capabilities and the procedure described in Section 3.4.3 the spatial extent of the flood waters was determined for each of the alternatives and a flooded feature image was produced for each of the alternatives. These images were used to compare and evaluate the alternatives using the Spatial Compromise Programming technique.

5.3 EVALUATION OF FLOOD IMPACTS

In order to evaluate and eventually compare the four potential alternatives, a method for measuring their effectiveness as flood protection strategies was required. To do so a number of impacts produced by flood waters, which were affected by implementation of the various alternatives, were selected and determined. Using the GIS component of the floodplain analysis model, the magnitudes of these impacts were estimated. Based on the accumulated total of these impacts for each alternative, the best solution for each location in the region of interest was determined with the Spatial Compromise Programming approach.

Selection of the criteria which were used to evaluate the flood protection alternatives was dependent on two factors. The first of these was the ability of the GIS to measure the impacts. The spatial extent of the flood waters was mapped within the flooded feature images produced by the floodplain analysis model. As a result impacts to specific features could be determined only if they had representation within these images. In addition, functions that could be used to relate impacts to features with flood attributes were required. The second factor which influenced selection of the criteria were the decision makers' preferences. The decision makers represented the interests, and values, of all people directly affected by implementation of the various flood protection measures. Determining flood water impacts of no concern to decision makers for the study region would not be useful. As there were many groups of people, which could be affected to different degrees by the alternatives, there were many individual concerns to consider. In selecting the criteria, attempts were made to accommodate as many different decision maker preferences and opinions as possible.

As there were a number of criteria to consider, evaluation of the alternatives required the application of MCDM techniques. The Compromise Programming and Spatial Compromise Programming techniques were used in the case study. The Spatial Compromise Programming technique uses the spatial analysis capabilities of GIS to determine the best alternative for each location in the region of interest. Necessary as input for the application of this approach are the criteria values, or impacts, produced by each of the flood protection alternatives as well as the decision makers' preferences. To meet these requirements the floodplain analysis model was used to prepare the needed information in a form appropriate to the Spatial Compromise Programming technique.

Because the Spatial Compromise Programming technique is applied using GIS, the criteria values for each alternative had to be represented in the form of raster images. Each cell of an image contained the magnitude of the impact for that location that resulted from implementation of a given alternative. If a given cell, or location, were not impacted by flood waters, it contained a value of zero. The criteria values for each alternative were determined by applying a combination of both GIS commands and external programs to the flooded feature images and DEM for the study area.

Three criteria were selected for purposes of evaluating the alternatives. These criteria are described next. The computational procedures necessary to produce the criteria images are also outlined. The exact GIS commands and external programs used for producing the criteria images are found in Appendix C.

5.3.1 FLOOD WATER DEPTH

The first criteria used in the evaluation of the alternatives was the flood water depth for the study region. An image was prepared in which each raster cell contained the water depth for all distinct geographic locations within the region of interest. This was accomplished using a combination of the flooded feature image, the water surface elevations as contained in the reach image, and the DEM for the St. Adolphe region. For all flooded areas, as indicated by the flooded feature image, the ground surface elevations in the DEM were subtracted from the calculated water surface elevation for each reach. Raster cells in locations which were unaffected by flood waters retained a value of zero. In this way an image containing the water depths for all flooded locations in the study region was produced for each alternative.

The Spatial Compromise Programming technique also required separate images showing the extreme optimal and worst criteria values for each location in the study region. For the flood water depth criteria, the absolute minimum water depth was considered the optimal criteria value. Actual maximum flood water depths were used to represent the worst criteria values. The absolute minimum flood water depth was zero. Thus the image indicating the minimum flood water depth for each location had a constant value of zero throughout the entire study region. Because actual extreme values were used for the maximum flood water depth image, this image was spatially variable. The values contained in the flood water depth images for each alternative were compared. The maximum value for each individual geographic location, or raster cell, between the alternatives was extracted and placed in a separate image. This final image produced showed the actual maximum flood water depths for each location for the St. Adolphe region.

5.3.2 BUILDING DAMAGE

The second criteria used in the evaluation of the alternatives was the dollar value of damage to flooded structures within the region of interest. As there were three classes of buildings represented in the feature image (i.e., industrial, municipal, and residential), damage could be determined for each type separately. Damage to each of the buildings was calculated through application of a stage-damage curve. This curve identified damage to the structures as a function of flood water depth. The flood water depths for all locations in the region of interest were determined for the previously discussed criteria. Damages to submerged structures were calculated by applying the stage-damage curve to each flooded building using the flood water depth images.

Stage damage curves for buildings located in the Red River Valley had been developed in 1983 by ECOS Engineering Services Ltd. and were available. They were based on actual insurance claims from, and public surveys pertaining to, the historic 1979 flood for this region. The damages indicated by the developed curves represented average values for all general types of residential buildings (i.e., bungalow, two-story, etc.) located in this area. The curves relate the flooded depth of a building to damage incurred as a percent of its total worth (i.e., structural and contents). However, the flood depths used to develop the curves included both flooding to the basement level of the structure, if one existed, and the depth of water above the ground surface. As the prepared flood water depth images only contained information on the level of water above the ground surface, modification to the ECOS stage-damage curves was necessary.

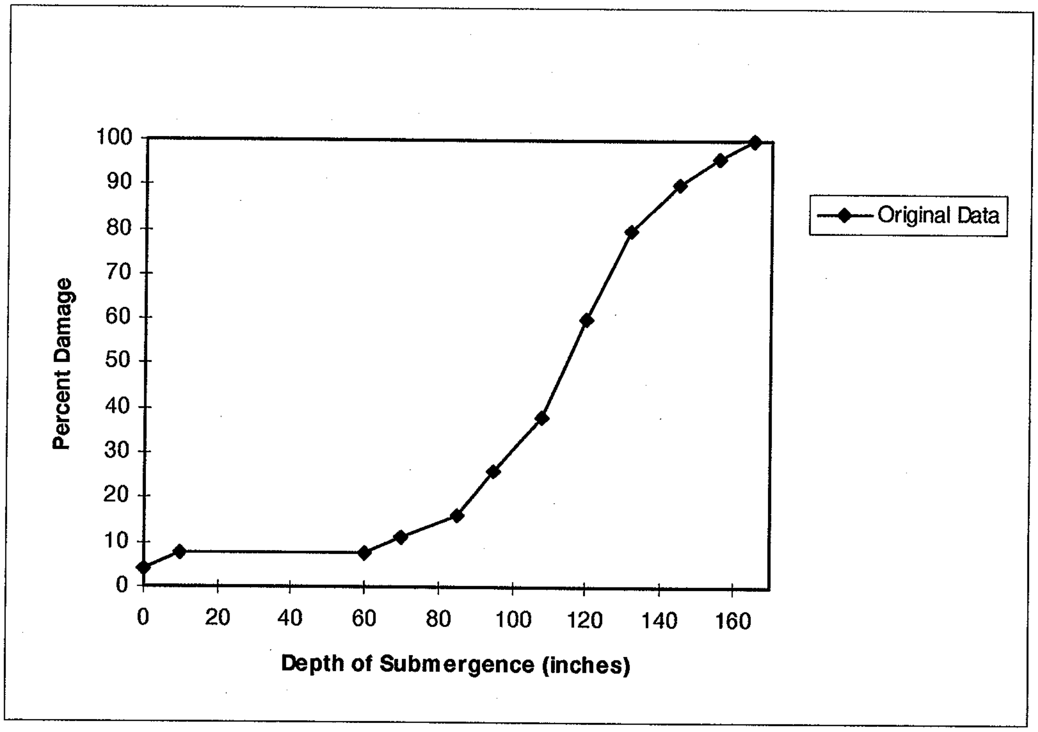

Figure 16: ECOS Stage-Damage Curve

The original stage-damage curve developed by ECOS for residential structures in the Red River Valley is shown in Figure 16. Through observation of this curve a large transition at approximately eight percent damage from ten to sixty inches depth of submergence is noted. Based on information in the surveys used in the ECOS study, the mean flooded basement depth for submerged structures in the 1979 flood was approximately sixty inches. Consequently damages incurred by structures up to this level were predominantly due to basement flooding. Further, damages to the buildings occurred when the flood water depth exceeded sixty inches. These damages were assumed to have occurred to the main level of the structures. It was concluded that the portion of flood water depth above the sixty inch level was approximately the depth of water above the ground surface outside the building. Removing the large transition from the ECOS curve, the resulting relationship would indicate damages to structures based on the outside, or above ground, depth of submergence. The resulting modified curve is shown in Figure 17. In order to simplify application of this curve in the case study, an equation describing the stage-damage relationship was developed using regression analysis. This new regressed curve is also shown in Figure 17. Though production of this curve was somewhat unorthodox, the stage-damage relationship produced is very similar to those used in Helweg, 1985.

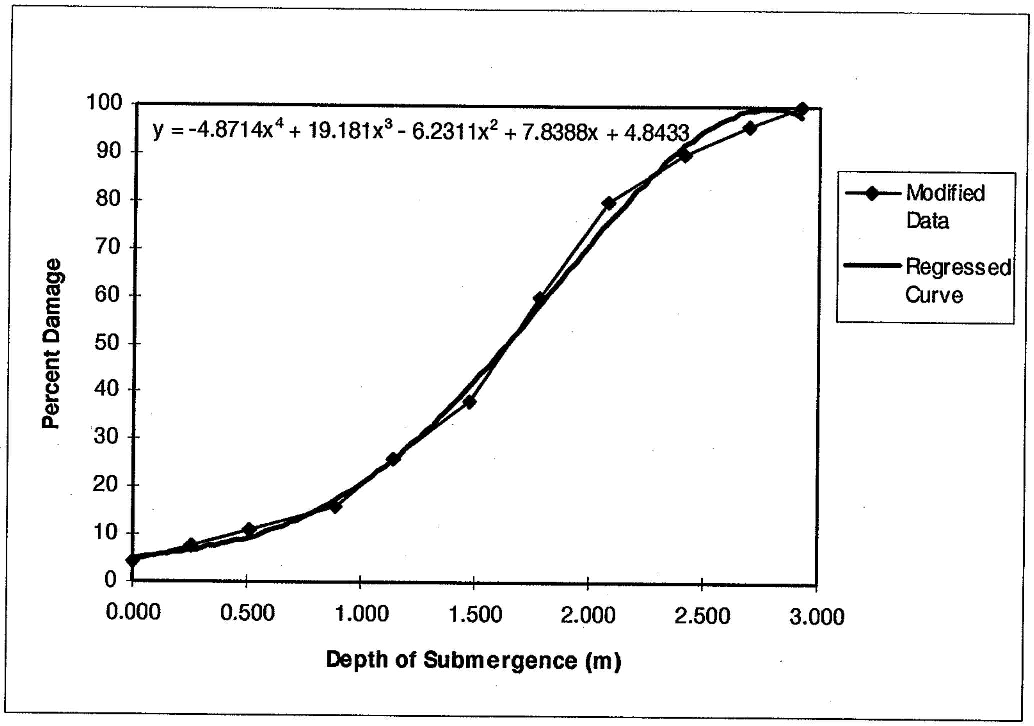

Figure 17: Modified Stage Damage Curves

Using this modified stage-damage curve, an image representing damages to flooded buildings in the study region was produced for each alternative. Submerged buildings were identified first using the flooded feature images. The depth of submergence for each building was determined by averaging flood water depths in the locations of individual flooded structures. Water depths for these locations, or cells, were taken from the flood water depth images. Using a combination of GIS commands and external FORTRAN programs the stage-damage curve was then applied to all classes of buildings. The resulting image showed the percent to which the buildings had been damaged. In this image, the cells corresponding to locations of the flooded buildings contained the percent damage for each structure. For example, if a particular building, composed of four raster cells, had been damaged to eighty percent of its total value, each cell in the building's location contained a value of 0.8. In order to calculate the amount of damage to the structures, each of the cells containing percents values were multiplied by the dollar value of building to which they corresponded. To capture the variation in the types of structures in the study region, each class of building was assigned a different dollar value indicating its relative worth. Estimated values for the residential, municipal, and industrial building classes used in this study were $50 000, $100 000, and $200 000 respectively. Multiplying these values by the percent damage to each structure produced an image showing the dollar value of damage to the buildings. Returning to the above example, each of the four cells of the building damaged to eighty percent would contain a value of 80 000 if the structure were a member of the municipal class. This image is incorrect however, as it implies that each of the four "municipal building" cells received $80 000 damage from the flood waters. To alleviate this inaccuracy the damages to each building were divided by the number of raster cells which comprised the individual structures. Referring once again to the same example, the cells corresponding to the location of the municipal building damaged to eighty percent would now contain values of $20 000. Thus, this final image produced contained the dollar value of damages incurred by flooded buildings for each location in the region of interest. Cells which either did not contain a building, or contained a non-damaged building, were assigned a value of zero. Once again, one of these images was produced for each alternative.

The Spatial Compromise Programming technique required images containing the optimal and worst building damage value for each location. For building damage criteria the absolute minimum damage values were used to represent the optimal criteria values. Actual maximum building damages were used to represent the worst criteria values. As this is the same as the flood water depth criteria, the identical procedure, as discussed in Section 5.3.1, was used to produce images indicating the minimum and maximum dollar value of damages incurred by buildings for each location in the study region.

5.3.3 BENEFIT OF FLOODING UPSTREAM AREAS

The final criteria used in the evaluation of the alternatives was a measure of the benefit of flooding the upstream communities. As previously discussed, often upstream communities, such as St. Adolphe experience increased flooding when the floodway is operated in such a manner to reduce damages in the City of Winnipeg. Thus, from an economic standpoint it is suggested that there is a benefit associated with flooding the upstream areas. The more water that is stored further away from the City of Winnipeg, by flooding the upstream areas, the greater the benefit, or reduction in downstream damages.

The magnitude of this benefit is a function of the volume of water stored upstream, and the distance of the stored water from the City of Winnipeg. The amount of water stored upstream resulting from implementation of each of the flood protection alternatives is shown in the flood water depth criteria images. Within these images each 5 x 5 m raster cell contained a value which corresponds to the water depth for that particular geographic location. Thus, the volume of water in each location in the study region is known. The distance of this water from the City of Winnipeg was determined using the hydraulic reach image. As previously stated, for the hydraulic modelling component of the floodplain analysis model, St. Adolphe and the surrounding area were divided into six distinct reaches. The reaches were numbered from one to six, starting at the furthest downstream location in the images. The relative distance of the water from the City of Winnipeg in each flooded location, or raster cell, was determined based on which hydraulic reach it was located. Using the information provided by the flood water depth images, in combination with the hydraulic reach image, the benefit of flooding upstream locations can be determined. The actual magnitude of the benefit associated with flooding upstream areas was calculated by multiplying the flood water depth in each raster cell by the reach number in which it was located. In other words, cells flooded to an equal elevation in the first reach produced lesser benefit than those in the sixth. Using this procedure, an image showing the benefit of flooding all locations in the study region was produced for each alternative.

Images identifying the optimal and worst benefit associated with flooding upstream areas were required. For the benefit criteria, the minimum value of benefit for each location represented the worst criteria value. The optimal criteria value was represented by the maximum benefit for each location. Similar procedures as those described in Section 5.3.1 were used to develop these extreme criteria value images.

5.4 EVALUATION OF FLOOD CONTROL ALTERNATIVES

The best mitigation strategy from the four potential flood protection alternatives for the St. Adolphe was determined, on the basis of the criteria described in Section 5.3. Using both the Compromise Programming and Spatial Compromise Programming techniques, each of the four flood protection alternatives were evaluated. Compromise Programming suggested a best alternative from the potential set of solutions based on criteria values for region as a whole. With the Spatial Compromise Programming approach, spatial variation in the criteria was accounted for, and the best alternative for each location in the region of interest was determined.

Weights indicating the relative decision maker preferences towards the criteria and the importance of their maximum deviation from the ideal solution were necessary input for both Compromise Programming and Spatial Compromise Programming. The importance of the deviation of criteria from their ideal values was reflected in the selection of the variable p in Equations (1) and (2). In this case study, for both Compromise Programming and Spatial Compromise Programming a single value of p=2 was used in the evaluation of all alternatives. Selection of this value was based on the results produced by Simonovic, (1989). In that study it was determined that a selection of p=2 could be used as a reasonable approximation of the best compromise alternative from a set of potential solutions.

A second set of weights was required to describe the decision makers' preferences towards the various criteria. These weights are symbolized as w_i in Equations (1) and (2). In order to represent the potential different opinions of the various groups of interested decision makers in the case study, three different sets of weights were selected and are shown in Table 3.

Table 3: Weights w_i Indicating Decision-Maker Preferences

Criteria	Decision-Maker Preferences (w_i)		
	Weight Set #1	Weight Set #2	Weight Set #3
Flood Water Depth	0.25	0.20	0.30
Building Damages	0.50	0.50	0.50
Benefit of Flooding	0.25	0.30	0.20

In all three set of weights, regardless of which decision maker's interests they represented, the criteria measuring damages to submerged structures was given the highest priority. Normally, in selecting weights, one set contains values indicating equal treatment of all criteria. However, because of the importance of the building damage criteria, this practice was not followed in this study. In evaluation of flood protection alternatives using conventional methods such as computation of Expected Annual Damage (EAD), damage to buildings is typically the only criteria considered. For this reason it was decided that this criteria should always have the largest weight, indicating building damage as the most important criteria.

With regard to the two remaining criteria, in the first set of weights they were assigned an equal level of importance. The other two sets of weights attempted to represent the differences in opinion and interests between the upstream and downstream communities. In the second weight set a greater emphasis was placed on the criteria measuring the benefit associated with flooding the upstream communities. This weight combination represented the interests of downstream communities as it emphasized selection of an alternative which would provide a greater level of flood protection for the City of Winnipeg. The final set of weights was the reverse of the second. This weight set represented the interests of upstream communities as it placed importance on minimizing the flood water depth in the St. Adolphe region.

5.4.1 COMPROMISE PROGRAMMING ANALYSIS

Using the weight sets contained in Table 3, and the calculated criteria values, the best alternative for the region of interest as a whole was first determined using the Compromise Programming technique. Before the best alternative could be selected, the criteria values for each flood protection alternative, in the GIS criteria images, had to be converted into a format which could be used with this technique. As Compromise Programming does not account for spatial variation of the criteria values, the values contained within the criteria images had to be accumulated across the entire region of interest. For the flood water depth and benefit of flooding upstream areas criteria, an average value was taken across the region. This was accomplished by summing the values for all impacted locations, or raster cells, in the criteria images and dividing the sum by entire area of the region. For the criteria used to measure impacts to submerged buildings, the total dollar value of damages to all structures in the St. Adolphe region were determined. This was accomplished by adding the damages to all locations, as contained in the building damage criteria images, for each alternative. Thus, for each of the three criteria a single number representing the impacts produced by each flood protection alternative was calculated. The resulting values are shown in Table 4. It should be noted that these values are not necessarily accurate, and may not represent the actual impacts associated with the 1979 flood for St. Adolphe region. Regardless, the criteria values may still be used to accurately identify the relative differences between the various alternatives.

Table 4: Spatially Invariable Criteria Values

Alternative	Compromise Programming Criteria Values		
	Flood Water Depth (m)	Building Damage ($)	Flooding Benefit (m^4)
1	0.96	18 630 000	30.83
2	0.91	19 644 500	29.06
3	1.01	19 632 000	32.51
4	0.91	7 765 000	29.52

Using the criteria values shown in Table 4 and the weights discussed above, each of the potential flood protection alternatives was evaluated using Compromise Programming. Based on Equation (1), a distance metric was calculated for each alternative. In comparing the alternatives the one with the smallest distance metric value was selected as the best. The results of the evaluation using Compromise Programming are shown in Table 5. As shown by the rankings, alternative four was determined to be the best flood protection strategy for the St. Adolphe region for all different weight combinations.

Table 5: Compromise Programming Rankings

Alternative	Weight Set #1		Weight Set #2		Weight Set #3	
	L_i	Rank	L_i	Rank	L_i	Rank
1	0.5296	2	0.5103	2	0.5523	2
2	0.5482	3	0.5319	3	0.5676	3
3	0.5583	4	0.5377	4	0.5824	4
4	0.2991	1	0.2678	1	0.3336	1

5.4.2 SPATIAL COMPROMISE PROGRAMMING ANALYSIS

Using the criteria images and the sets of weights shown in Table 3 each of the potential flood protection alternatives was evaluated with the Spatial Compromise Programming technique. The first step toward evaluating the alternatives was the production of a distance metric image for each alternative. This was done by applying the distance metric formula shown in Equation (2) to the criteria images using GIS commands. The resulting images contained a distance metric value in each raster cell that corresponded to the relative impact produced by each alternative for that particular geographic location. All calculations and GIS commands needed for the evaluation and comparison of the flood protection alternatives are found in Appendix C. The distance metric values for each location in the study region were compared between the four potential alternatives. The alternative corresponding to the highest distance metric value for each location was typically selected as best. In comparing the distance metric values for distinct geographic locations, however, ties often occurred between the alternatives. This was due to a lack of variety of criteria, limitations with respect to the type of potential alternatives which could be produced by the floodplain analysis model, and internal rounding of distance metric values by the GIS commands. Ties between alternatives were resolved internally by the GIS command used to compare the distance metric values for each location. As a function of the GIS module (MDCHOICE), the alternative first considered in the comparison was selected as best. As a result, the order in which alternatives were compared had the possibility of influencing the ranking of alternatives for each location.

Based on the comparison of distance metric values, a best alternative image for the study region was produced for each set of decision maker preferences. Contained in each raster cell within these images was the number corresponding to the best alternative for each location. A sample of the best alternative image, for each of the three respective sets of decision maker preferences, is shown in Figures 18, 19 and 20. The specific area within the study region encompassed by each of these three figures corresponds to the feature image shown in Figure 15.

As can be seen by the variation in the images in Figures 18, 19 and 20, the selection of decision maker preferences has a significant effect on the outcome of the evaluation. A number of general observations regarding the effectiveness of the potential flood protection alternatives for various locations in the region of interest can be made. In each of the three attempted sets of decision maker preferences, alternative one generally proved to be the best for locations corresponding to buildings outside of the town of St. Adolphe. As alternative four called for complete protection of St. Adolphe, this was the best flood protection strategy for locations within the town occupied by structures. Alternative three was generally ineffective as a mitigation strategy.

Many locations in the study region, in and outside the town of St. Adolphe, did not contain specific features, and consisted predominantly of uninhabited areas or farmland. The best alternative for these areas changed frequently, depending on the decision makers' preferences towards the flood water depth and benefit of flooding upstream areas criteria. With the first set of weights, having the flood water depth and benefit of flooding upstream areas criteria treated equally, the best alternative for these areas was predominantly alternative two. This is shown in Figure 18. Alternative two provided the smallest overall flood water depth for the entire region of interest. As a result selection of this alternative as best for locations outside the town of St. Adolphe seems logical. The uninhabited areas within the town boundaries, however had the option of being fully protected by the ring dyke offered in alternative four. Regardless, alternative two was still selected as best for areas within the town which did not contain buildings. This was due to the decision maker preferences towards the criteria. In light of the benefits associated with flooding upstream areas, it was determined that flooding locations within the town which contained no structures was the best flood protection strategy.

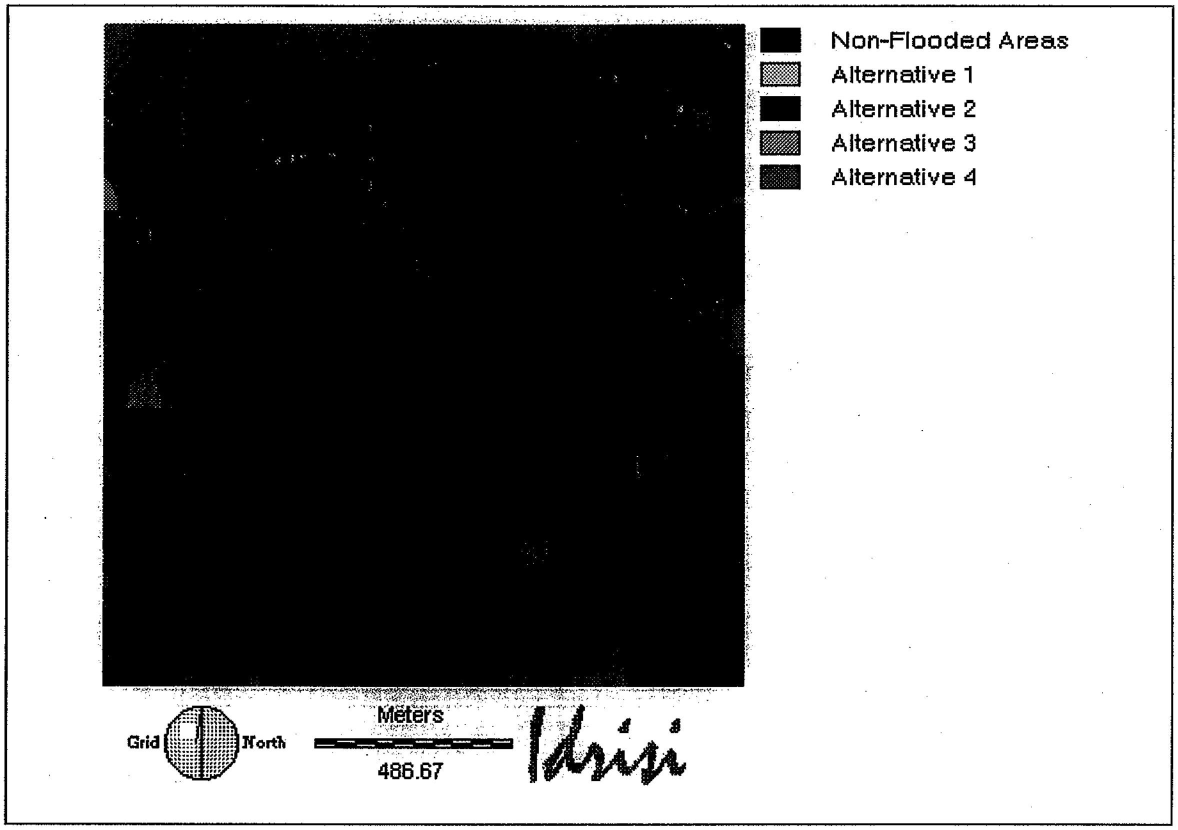

Figure 18: Best Alternative Image for Weight Set #1

The second set of weights represented the interests of the downstream region. As a result in the evaluation of the potential flood protection strategies the preference would be for those alternatives which forced a larger volume of water upstream of the Red River Floodway. The effects of this change in decision maker preferences are noted in Figure 19. Areas for which alternative two was selected as best using the first set of weights, are now better satisfied by alternatives one and four. These two alternatives correspond to a slightly greater overall depth of flood waters in the St. Adolphe region. This is the reason for their selection in certain areas, in the study region, given the second set of decision maker preferences.

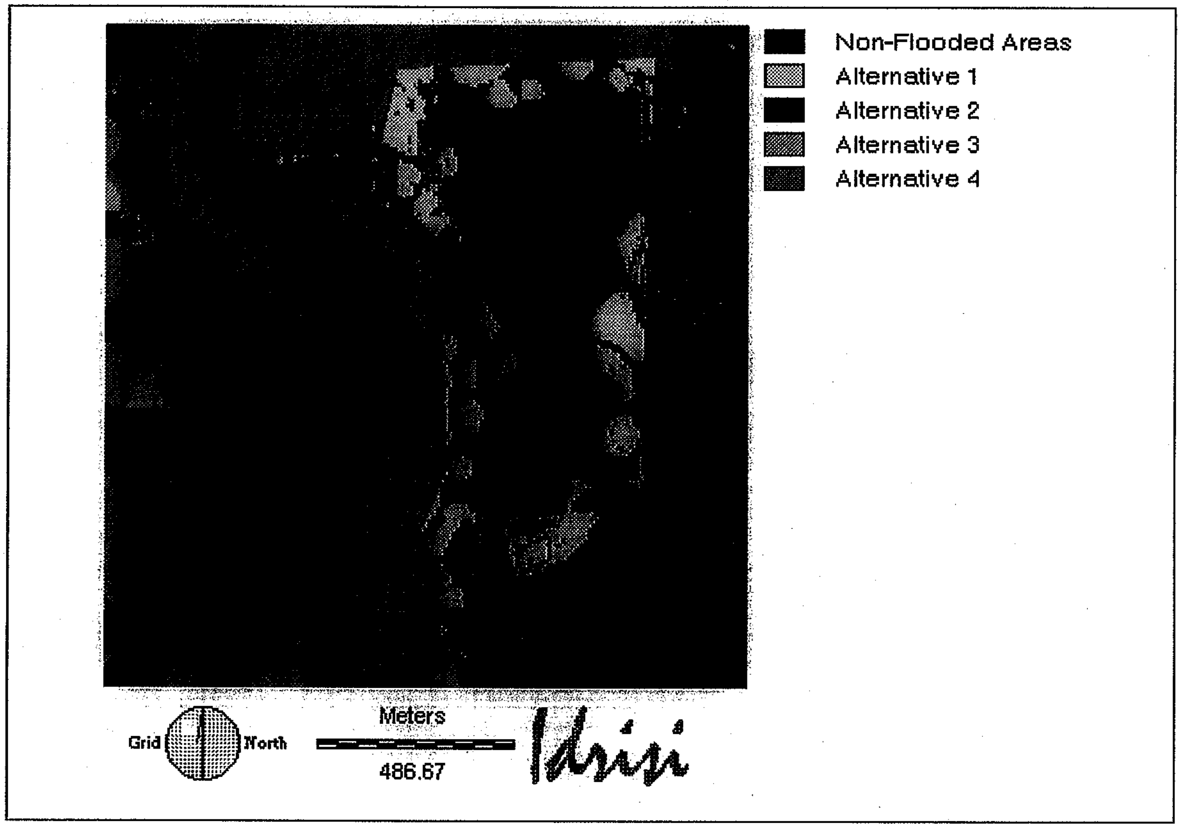

Figure 19: Best Alternative Image for Weight Set #2

The final set of weights used in the evaluation of the potential flood protection alternatives placed a greater emphasis on minimizing the flood water depth, in contrast to the benefit associated with flooding the region of interest. This set of weights represented the decision makers' interests pertaining to the protection of upstream communities. In this case the alternatives selected as best for the study region were those that minimized the overall volume or depth of flood waters in upstream areas. As a result, for almost all locations within the town of St. Adolphe, as shown in Figure 20, alternative four was selected as the best. This is logical as the ring dyke used in this alternative was constructed to an elevation such that it eliminated flooding in the community. For uninhabited areas outside St. Adolphe, because alternative two offers the lowest overall flood water depth, it was predominantly selected as the best.

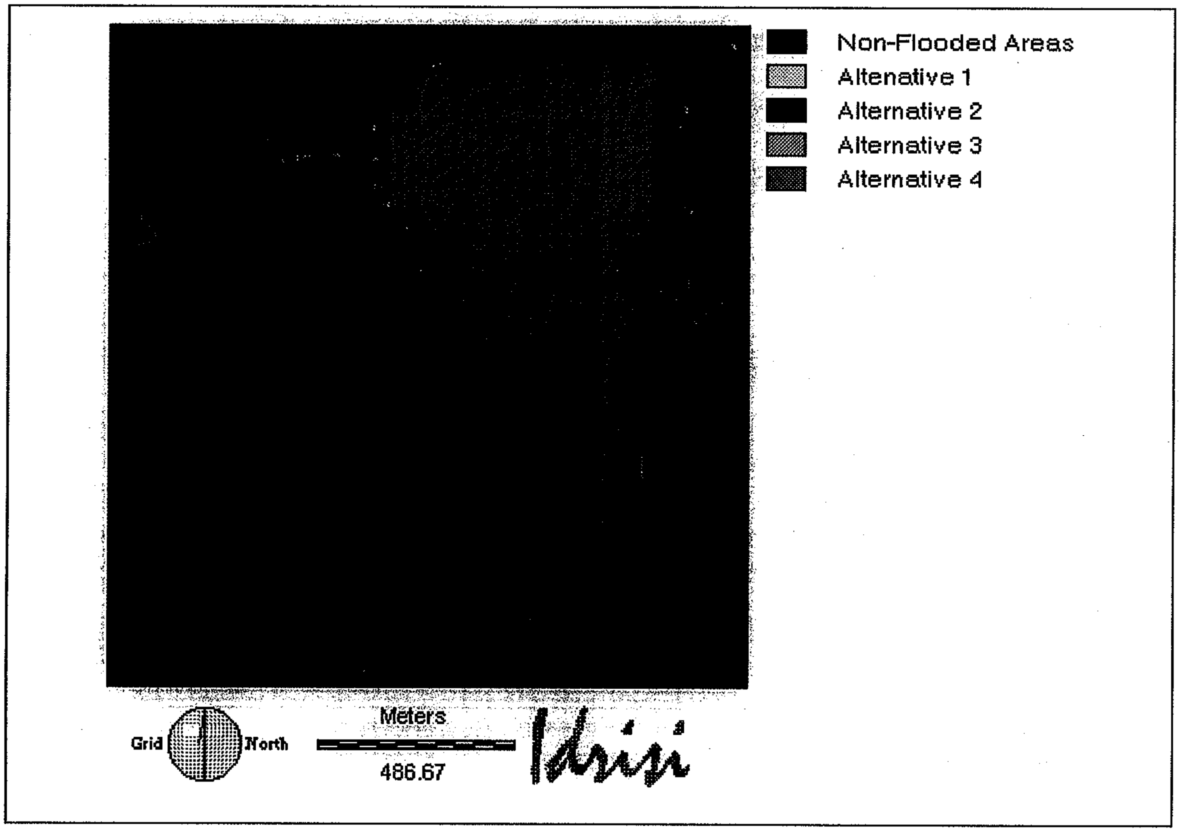

Figure 20: Best Alternative Image for Weight Set #3

5.5 EVALUATION SUMMARY

Through application of the Spatial Compromise Programming technique with GIS technology, the best flood protection strategy from a set of potential alternatives was determined for all locations in the case study area. Spatial Compromise Programming provided decision makers with more detailed and useful information important to the evaluation of the alternatives. As was shown in the case study through the use of conventional Compromise Programming, flood protection alternative four was clearly the best for all sets of decision maker preferences. However, as indicated by the best alternative images created using the Spatial Compromise Programming technique it is shown that this strategy may not necessarily be the best for all locations in the study region. By maintaining the spatial variability of the criteria values, localized impacts associated with each alternative could be determined with this new technique.

In analyzing this information, potential sources of conflict between various groups of decision makers could be identified. Application of the Spatial Compromise Programming approach could ultimately lead to better decision making in the field of water resources.

6. CONCLUSIONS

Many types of analyses in the field of water resources require the use of spatially distributed information. GIS is an effective tool whose main function is to store, process, manage, and analyze spatial information. GIS has facilitated many types of water resources analyses in many different ways. Illustrated by the case study in this thesis are two practical applications of GIS in the field of water resources. These two applications involve the use of GIS for the purpose of floodplain simulation as well as for MCDM in the field of water resources.

The first major use of GIS in this research was in the development and implementation of the floodplain analysis model. This model was used to simulate flooding in the St. Adolphe region based on the theoretical implementation of different flood protection alternatives. The GIS had three distinct roles in the floodplain analysis model: a) the determination of flood water extents; b) the generation of different flood protection alternatives; and c) the calculation of impacts produced by flood waters.

In order to determine the flood water extent in the St. Adolphe area, GIS was linked with the conventional hydraulic model HEC-2. Water surface elevations for the selected magnitude of flooding event were determined by the hydraulic model. These elevations were then transferred to the GIS. Using the calculated water surface elevations, the flood simulation algorithm developed by Bender and Simonovic (1995), and GIS images describing the characteristics of the area (i.e., the feature image and DEM), the flood water extents in the St. Adolphe region were determined. By combining GIS with the hydraulic model, the determination of flood water extent was more accurate than it would have been based on the use of HEC-2 alone.

The GIS was also used to generate a set of potential flood protection alternatives for the St. Adolphe region. The physical characteristics of the St. Adolphe region were contained in the GIS database. By changing these characteristics in the database, new flood protection alternatives for the region were generated. Using the floodplain analysis model, the flood water extent was then determined based on implementation of the new generated alternatives.

Having generated a set of potential flood protection alternatives for the St. Adolphe region, their effectiveness at mitigating floods had to be determined. In order to do so the impacts produced by flood waters resulting from implementing the various alternatives were calculated. The analysis capabilities of GIS were used to perform this task. Features in the St. Adolphe region affected by flood waters were identified first. Damages to the features were then calculated based on the degree to which they were affected by the flood waters. In so doing the flood impacts produced by, or associated with, each of the generated alternatives were determined. The alternatives were evaluated based on the magnitude of these impacts.

For the case study three different types of flooding impacts were determined using the floodplain analysis model, and used as criteria for evaluating the alternatives. The decision maker preferences regarding the importance of the criteria were also accounted for, in the evaluation of the alternatives. In the case study, decision makers represented the interests of two distinct groups of people affected by the flood control alternatives. These were the residents of the upstream and downstream communities. Because multiple criteria and decision maker preferences had to be considered, evaluation of the alternatives was complex. Thus MCDM techniques were used to assist in the evaluation of the flood protection alternatives.

The values of the flooding impacts associated with each of the generated alternatives were spatially variable. In order to evaluate the alternatives accurately it was necessary to take this variability into consideration. Since conventional MCDM techniques do not take the spatial variability of criteria values into consideration a technique which maintained the spatial variation of the criteria values was developed. This technique was called Spatial Compromise

Programming. The technique was developed by embedding the conventional MCDM technique Compromise Programming within a GIS framework.

Both Compromise Programming and Spatial Compromise Programming were used to evaluate the potential flood control alternatives for the case study. The objective of the evaluation was to identify that alternative which most reduced the impacts produced by flood waters. The MCDM techniques were incorporated to assist in selecting the best flood protection alternative from the generated set for the case study area. Using Compromise Programming it was determined that alternative four offered the greatest level of flood protection to the region. This evaluation was based on the criteria values associated with the alternatives and all attempted sets of decision maker preferences. In this evaluation the criteria values which were used represented impacts produced by flooding as they were incurred by the St. Adolphe region as a whole.

The potential flood protection alternatives were also evaluated using the Spatial Compromise Programming technique. Using this technique the best alternative for each distinct location in the St. Adolphe region was determined. By doing so it was noticed that alternative four, which was selected as the best by Compromise Programming, was not necessarily the best alternative for all areas in the region. It was determined that alternative four provides a high level of flood protection for the town of St. Adolphe only. Areas outside of the community would receive greater flood protection through implementation of the other available alternatives. It was also determined that choice of the best alternative for many locations was very sensitive to the decision maker preferences. Changing the weights that indicated the relative importance of the criteria altered the results of the evaluation. This information was not apparent from the evaluation of alternatives using the Compromise Programming technique.

Localized impacts such as those produced by alternative four in the case study could be detected using the Spatial Compromise Programming technique. This is accomplished by maintaining the spatial variability of the criteria values in the evaluation of the alternatives. By applying the Spatial Compromise Programming technique, decision makers would be provided with useful information regarding the locations which incur positive and negative impacts due to implementation of the various water resources projects. Knowledge of this type of information could lead to better decision making in the field of water resources.

7. FUTURE RESEARCH

The research described in this thesis could benefit from future work. The following is a description of several possible improvements and additions which could be made to this research in order to increase its potential application.

The accuracy of the analyses performed in the case study could be improved by obtaining and implementing more reliable data than that which was used in this research. Specifically, the data used for the GIS component of the floodplain analysis model requires improvement. As previously mentioned, a portion of this data was obtained by processing of three-dimensional aerial photographs at a scale of 1:20 000. Due to this large scale, many errors were made in interpreting the photos. This resulted in the misclassification of features in the case study region. Also, the elevations of many of the features were incorrect. These errors in the data could be reduced by obtaining aerial photos of the region at a much smaller scale. Aerial photos of the Red River Valley have already been taken at a scale of 1:5 000 and are presently being processed. When this information becomes available, the database used for the case study analysis should be updated.

Improvements could also be made to the DEM portion of the GIS data set. The method of producing DEMs for this research was somewhat unorthodox. As a result, the accuracy of the DEMs is open to question. In order to improve the DEMs they should be reproduced using the 1:5 000 scale data discussed above. At the smaller scale, the distribution of the data points obtained by processing the aerial photos would be more even. Application of interpolation routines to the new data would produce better results than those that were obtained in this research.

To further improve the GIS component of the research, new software should be selected. The IDRISI software was very affordable and was an excellent tool for educational purposes. However the accuracy of its analyses was questioned many times throughout the research. Often the results generated through GIS analyses were randomly incorrect in many ways. Features contained in the images had been shifted either horizontally or vertically at random. Also, numerical results obtained through application of simple mathematical expressions using GIS commands were often incorrect. Selection of a more reliable GIS software could reduce these random mishaps.

In the evaluation of the flood protection alternatives only three criteria were used. In order to obtain a more accurate evaluation of the alternatives the number of criteria used for their evaluation should be increased. By doing so the total impacts produced by flooding could be accounted for in the evaluation. In order to use more criteria in the evaluation of the alternatives, additional impacts produced by flood waters require determination. Impacts incurred by many different types of features such as roads, bridges and recreational areas within the flood plain could be calculated. These impacts could be determined from many different perspectives including economic, environmental, or social. In order to determine these different impacts, new relationships correlating damages to specific features with flood characteristics (i.e., water depth, water velocity, duration of submergence, time of year of flooding, etc.) would have to be developed.

A major issue in flood control at present is the question of "who should pay for the development and implementation of flood protection measures?". Flood control alternatives are often paid for by all people residing in the general location in which they are implemented. However as shown in the case study not all people benefit equally from the implementation of flood control measures. Should only the people who receive benefits from the measures pay? Should all people in the region pay equal amounts regardless of the protection which they receive? These questions were not easily addressed in the past due to a lack of knowledge pertaining to the localized impacts produced by flood waters. Using the Spatial Compromise Programming technique the people benefiting from implementation of the various alternatives can be identified. This information could potentially be of assistance to decision makers when determining who should pay for flood protection. The application of the Spatial Compromise Programming technique for this purpose should be investigated.

Finally, the evaluation of the potential flood protection alternatives performed in the case study requires improvement. Only three sets of decision maker preferences were considered n the evaluation. Additional sets of weights indicating different preferences towards the criteria should be considered. Also, in the evaluation of the alternatives, the complete compromise set of alternatives was not generated through application of either the Compromise Programming or the Spatial Compromise Programming techniques. In order to provide an accurate assessment of the alternatives, the complete approximation to the compromise set should be generated by including the weight values of $p=1$ and $p=\infty$ in the evaluation.

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APPENDIX A: IMAGE PROCESSING PROCEDURES

A. IMAGE PROCESSING PROCEDURES

Data describing the characteristics of the Red River Valley was required by the floodplain analysis model in order simulate flooding in the region as well as to generate and evaluate new potential flood protection alternatives. The necessary data were available and had been generated via three means: processing three-dimensional aerial photographs (1:20000 scale); conventional land surveying; and digitizing topographic maps. The original data was stored in DXF file format. It was organized on the basis of geographic locations in 10 x 10 km units referred to as tiles. Each tile contained the characteristics of between 30 to 200 types of features, or layers, and had an approximate file size of 20 MB in DXF format. Twenty-eight of these tiles were obtained and processed into raster feature images and DEMs.

Before the data were to be converted from their original form to useful raster images showing features and their elevations, a cell resolution had to be selected. In order to perform analyses using both the feature images and the DEMs, raster GISs require that both images have the same cell size. Consequently a common resolution had to be decided. The decision made was based on three major factors. The first issue to be considered was the level of accuracy required to represent the study area. As the image cell size increased the level of image detail decreased. If the chosen cell size was too large the level of accuracy of the analysis performed could decrease significantly (Zhang and Montgomery, 1994; Wolock and Price, 1994). However, as the cell size being considered decreased two negative outcomes occurred. First, with a decrease in cell size, more cells were required to represent the same area. Consequently the file size of the images, and so the database increased. Secondly the larger database would increase the computation time required for the production of DEMs and the analyses as well. In consideration of these factors it was decided that a 5m cell resolution was appropriate. The higher quality of image detail at this cell resolution would offset the negative implications of having a larger database and increased computation time.

A.1 FEATURE IMAGES

The feature image was a necessary input to the GIS component of the floodplain analysis model. It was used to identify the geographic location of natural and man-made physical characteristics of the study area. Raster feature images were produced individually for each 10 x 10 km tile in the case study area. In order to produce these images the data had to be converted from their original DXF format. This conversion required a multistage process because the IDRISI software could not produce raster images directly from DXF files. The software included a module (DXFIDRIS) for the purpose of converting data from DXF to a vector file format. When applied, this module produced a vector file which contained all layers of information available in the DXF file along with their individual identifiers. While in vector format all necessary sorting and editing of features was easily performed. All modifications to the feature data while in vector format were undertaken using the TOSCA digitizing software. Once the vector files had been appropriately prepared, all feature information was transferred to raster images.

A.1.1 Preparation of Feature Data

Before being converted to raster images, the vector files containing the feature data had to be edited for many reasons. As previously mentioned, in the data set obtained for this study up to 200 layers of qualitative features were available. The researcher decided that this level of detail was too great for purposes of the study. As a result all feature data deemed irrelevant to flood simulation or the multi-criteria decision making analysis performed in this research were eliminated from the data set. However, during this editing process caution was exercised against eliminating too much information. This discretion was based on the possibility of encountering unanticipated changes in information requirements for the research, and on the potential that future use of the data set for other studies in the field of water resources would require additional information.

Those features which remained were sorted into broad classes. The objectives in doing so were to further reduce the level of detail of the data and to create a consistent classification scheme for all feature images. The necessity for further reduction of detail were necessitated by the limited display capabilities of version 4.0 of IDRISI which was being used at this stage of the research. This early version of IDRISI had the ability to display up to a maximum of fourteen different classes of information at one time. The researcher concluded that it would be undesirable to be required to look at multiple screens in order to see all of the features for a single geographic location. For this reason the data had to be sorted into a maximum of fourteen broad classes of feature types.

The second objective in the creation of the broad classes was to develop a consistent content for each of the feature images. This consistency was necessary for two reasons. First, floodplain analysis required that feature images from multiple tiles be assembled as a single image. Second, in the development of the analysis procedures for the flood simulation the objective was to create a consistent set of commands (i.e., macros) which could be used to analyze any feature image. In both instances the desired actions would be possible only if all feature images contained similar types or categories of information as identified in each map's legend.

The features contained in each of the tiles were sorted into fourteen broad classes. Because some tiles contained greater level of detail than others, the classes created were intentionally very broad in order to assure that each class would be represented in the feature image for all tiles. Creation of the classes themselves was based on the availability of the types of information being classified and their relative importance to the flood simulation and multi-criteria decision making components of the research. Placement of detailed features into the broad classes was subjective, and was based on the author's assessment of their similarity to each other in consideration of the type of analysis being performed. A list of the classes, or map legends, for each feature image is found in Table 1. A description of the detailed features which were found in a single DXF file follows Table 1. Listed features without a hand written number beside the "feature description" were not included in the feature images. The features which were included in the feature image have a hand written number beside the "feature description" identifying the class in which the feature was placed.

Table 1: Feature Classes and Identifier Numbers

Identifier	Feature Classes
0	Background
1	River
2	Lake/Dugout
3	Marsh
4	Dyke/Dam
5	Bridge
6	Rail
7	Road
8	Trees
9	Industrial Buildings
10	Municipal Buildings
11	Residential Buildings
12	Hydroline
13	Parks/Recreation
14	Floodway/Canal

Output file AK36_A-D.DXF will have the following feature translations

(.DXF files have the layer names set equivalent to the CARIS feature names)

CARIS feature CODE (DXF layer name)	DXF Shape name	TOTAL # of items	Feature Description
AB33850110		7	YARD - AUTO WRECKER
AB33850130		10	YARD - JUNK/SCRAP/SALVAGE
AB33850140		12	YARD - LUMBER
AB33850150		1	YARD - STOCK
AB33850160		2	YARD - STORAGE (MAINTENANCE)
AG09850000		33	ELECTRICAL SUBSTATION COMPLEX
AG21275000		61	PILE
AG26800000		11	UNDER DEVELOPMENT
AL07500120		24	COURT-TENNIS
AL11750000		2	FORT
AL12350000		21	GOLF COURSE
AL13650000		2	HISTORIC AREA/SITE
AL13650000CM	CM	7	HISTORIC SITE
AL20150110		1	PARK-AMUSMENT
AL20150130		174	PARK-MUNICIPAL
AL21900000		127	PLAYING FIELD (SPORTS)
AL22000000CS	CS	4	POINT OF INTEREST
AL22650000		41	RACE TRACK
AL24800000		71	RINK (OUTDOOR)
AM04650000		16	CEMETERY
AN18100000		8	MOBILE HOME PARK
AP16450000		11	LIQUID WASTE DISPOSAL AREA
AQ13450000CR	CR	1	HELIPAD
AQ20400000		97	PARKING LOT
AR03400000		233	BUILT-UP AREA
BA12600001CE	CE	95	GRANARY (CIRCULAR)
BB12550000		2	GRAIN ELEVATOR
BB27050000		6	SHOPPING CENTRE
BE05900000		1	COLLEGE
BE26000000		139	SCHOOL
BE32400000		5	UNIVERSITY
BF05550000		3	CITY HALL
BF11000000		11	FIRE STATION
BF14900000		1	JAIL
BF16100000		1	LEGISLATIVE BUILDING
BF22000000		4	POLICE STATION
BF22250000		3	POST OFFICE
BG09750000		1	ELECTRIC POWER GENERATING STATION
BG09800000		36	ELECTRICAL SUBSTATION
BG10300000		10	FACTORY/PLANT
BG17450000		15	MILL
BG23650000		15	REFINERY
BH13950000		35	HOSPITAL
BJ01100000		1	ARMOURY
BL01050000		26	ARENA

BL01200000	56		1	ART GALLERY (PUBLIC)
BL01250001	61		1	CONVENTION CENTRE
BL05750001	22		33	COMMUNITY CENTRE
BL11250000	26		12	SPORTSPLEX
BL13700000	67		8	BUILDING HISTORICAL
BL17000000	73		5	MARINA
BL18900000	63		3	MUSEUM
BL21600000	70		3	PLANETARIUM
BL30100000	43		3	SWIMMING POOL (INDOOR)
BM03350000	20		175	BUILDING RELIGIOUS
BN09350140	35		65	DWELLING/OLD-AGE-HOME (INSTITUTIONAL
BQ30750000	72		1	TERMINAL/STATION
BR03300000	6		6937	BUILDING
CA12800000	62		20	GREENHOUSE
CB29700000	53		67	STORAGE TANK LARGE (VERTICAL)
CB29700000CE		CE	116	STORAGE TANK SMALL (VERTICAL)
CB29700100	44		9	STORAGE TANK (HORIZONTAL)
CC00850000AA		AA	2	ANTENNA
CC31150000AA		AA	2	TOWER/MAST
CG07600110	74		1	CRANE MOVEABLE
CG28300000AA		AA	13	CHIMNEY/SMOKE STACK
CL12650000	31		7	GRANDSTAND
CL20800000	63		3	PAVILION/SHELTER
CL30150000	25		20	SWIMMING POOL (OUTDOOR)
CQ06400000	41		22	CONVEYOR
CQ15800000CU		CU	2	LAUNCHING RAMP
CQ33450000	59		17	WHARF LARGE (PIER,JETTY,DOCK)
CQ33450001	60		2	WHARF SMALL (PIER,JETTY,DOCK)
CR29800001	51		42	CORRIDOR PEDESTRIAN (ELEVATED)
DA24900110	23		33	ROAD - U/C
DA25000121	3		89	ROAD (GRAV UNDIV) LESS THAN 2 LANES
DA25050191	19		1084	ROAD (P D) N ELE 2 LAN EA WAY ME<10M
DA25050192	29		738	ROAD (P D) N ELE 2 LAN EA WAY ME>10M
DA25050201	21		246	ROAD (P D) N ELE 3 LAN EA WAY ME<10M
DA25100190	1		555	ROAD (PAV UNDIV) - 2 LANES
DA25100191	27		405	ROAD (PAV UNDIV) - LESS THAN 2 LANES
DB00100000	2		2316	ACCESSWAY
DB00100120	13		2721	ROAD (BACK LANE)
DB00150000	7		854	ROAD (UNCLASSIFIED)
DB00200000	4		9230	ROAD (PAVED STREET)
DC31400110	3		112	CART TRACK
DC31700001	5		219	TRAIL(FOOTPATH,BICYCLE)
DD03100000	64		11	BRIDGE (PEDESTRIAN/CYCLE)
DD03150000	55		210	BRIDGE (RAILWAY)
DD03250000	39		152	BRIDGE (ROADWAY)
DD08000001CP		CP	6	CULVERT (ROADWAY, RAILWAY)
DD24600000	45		11	RETAINING WALL
DD32200000AT		AT	2	TUNNEL (SYMBOL)
DE22800001	37		46	RAIL LINE (ABANDONED)
DE22950150	11		1724	RAIL LINE (SINGLE TRACK) - TRAIN

Output file AK36_E-N.DXF will have the following feature translations

(.DXF files have the layer names set equivalent to the CARIS feature names)

CARIS feature CODE (DXF layer name)	DXF Shape name	TOTAL # of items	Feature Description
EA10850110		1	FILTRATION BED - WATER
EA16400000		24	TRANSMISSION LINE
EA21950119CE	CE	5	POLE - ELECTRICAL
EA31050110AA	AA	2	TOWER - WATER (HOLDING)
EA31200110CQ	CQ	190	TOWER/PYLON - ELECTRICAL
GA08800000		56	DITCH
GA08800009		632	DITCH (PARALL. & ADJA. ROAD OR RAIL)
GA24850150		16	RIVER/STREAM - INTERMITTENT
GA24850180		64	RIVER/STREAM - PERENN TIME OF PHOTO
GB09150000		2	DUGOUT
GB15300130		2	LAKE - INDEFINITE
GB15300140		3	LAKE - INTERMITTENT
GB15300180		13	LAKE - PERENNIAL - TIME OF PHOTO
GB22100001		29	POND (RETENTION ORNAMENTAL)
GB24300000		2	RESERVOIR
GC17100000		27	MARSH
GE07800000AM	AB	1	CRIB/BRIDGE PIER,ABANDONED
GE09400001		4	DYKE
HA06300000		233	CONTOUR (LAND) - INTERMEDIATE
HA06300121		503	CONTOUR (LAND) - SUPPLEMENTARY
HA06300130		68	CONTOUR (LAND) - DEPRESSION
HA06300131		1	CONTOUR (LAND) - DEPRESSION - INDEX
HA06300132		308	CONTOUR (LAND) - DEPRESSION - SUPPL
HA287000002D	2D	2602	SPOT HEIGHT
HA33100000CK	CK	6	WATER LEVEL
JA08400000		2	CUT LINE
JA25550000		147	ROW OF TREES
JA33750000		786	WOODED AREA
KA07950124		1	CULTURE TEXT - ANTENNAE
KA07950840		8	CULTURE TEXT - CHIMNEY/SMOKE STACK
KA07950885		1	CULTURE TEXT - TOWER/MAST
KA07950887		2	CULTURE TEXT - WATER TOWER
KA07950909		73	CULTURE TEXT - NEIGHBOURHOOD NAME
KA37950805		1	TEXT, TOWN MED, CITY SMALL
KB14250180		2	CULTURE TEXT - DITCH (DRAIN)
KB14250390		6	CULTURE TEXT - RIVER/STREAM
NEAT		1	NEAT LINE

The actual sorting of features was accomplished by replacing the individual labels for each feature layer as contained in the DXF file with a common identifier pertaining to the class in which it belonged. The selected identifiers for the features were the class numbers themselves as shown in Table 1. Having sorted the features, each vector file for each tile was separated into individual files for each class of feature. This was done to allow further editing and to assist in the creation of the raster images as discussed below.

After the features had been classified they were inspected for obvious errors. One of the more common errors discovered that required correction was the improper identification of specific features. Often a distinct feature would have the identifier of another object. For example, a house could have been misinterpreted as a lake. If the feature could be properly identified through visual inspection of the data its identifier was changed. If not, the feature was deleted.

One major correction to the feature information was required. In converting the data from DXF to vector format all polygon information had been lost and the vector files contained only points and lines. The floodplain analyses required that certain features contained in the raster images be represented by polygons. Consequently, those points and lines which were required to be polygons for purposes of the analyses were converted. The vector files for all feature classes were then broken down further into individual files containing points, lines, and polygons. A detailed list of the steps required to edit vector files and to convert features to polygons can be found in Appendix B.

A.1.2 Creation of Raster Features

Raster images can be produced directly from vector files but IDRISI requires that the vector points, vector lines, and vector polygons be converted to raster separately. The software provides three modules (POINTRAS, LINERAS, and POLYRAS) to be used for the conversion of each different feature format. Producing a raster feature image was accomplished by starting with blank image having the same dimensions and geographic positioning as the vector files being converted. The dimensions and coordinate locations for each feature image were dictated by the tile from which the image was being produced. In the blank image the initial value of each cell was zero. The features contained in the vector files were then superimposed onto the blank image, using one of the POINTRAS, LINERAS, and POLYRAS modules. By doing so the raster cells in the geographic location of the individual features were assigned the number of the feature identifiers.

Depending on the cell resolution, as well as on the spatial density of features, it is possible that more than one feature identifier could be assigned to the same cell. For example if the selected cell size in the raster image were 100 m, multiple different classes of features such as a buildings, roads, trees or dykes could potentially fit within this 100 x 100 m region. However, a raster cell could only retain the value of a single feature identifier. In the method of producing raster feature images being described, the feature identifier contained in the cell was dependent on the order in which the information was transferred to the image from the vector file. The value ultimately contained in any given cell corresponded to the last information received for that particular location. All other information which may have been contained within the cell area was lost. This was undesirable, in that large portions of the database could be lost in the conversion of features from vector to raster. If important fine details were lost, the level of accuracy of the analysis could decrease significantly. This degradation of information due to competition for representation between features in close proximity to each other was addressed in two ways. These were the choice of the cell resolution and the order in which the features were converted from the vector files to the raster images.

The choice of cell resolution strongly influenced the degree to which the data was degraded in the creation of the feature images. The smaller the cell size the less chance there was of assigning multiple identifiers to a single location. As a result there was greater potential for capturing fine details. The cell size should be small enough to capture the transitions in the data (Zhang and Montgomery, 1994). In order to determine the resolution required to produce the necessary level of detail for the analysis two issues were considered. These were the size and spatial density of the smallest features. After experimentation with cell sizes of 30, 20, 10, 5, 2 and 1 m, the researcher decided that a cell resolution of 5 m would provide ample detail while not having unacceptable negative implications.

The order in which the features were converted from vector to raster was of great importance. Though care was taken in the selection of the cell resolution to ensure that only a single feature identifier would be assigned to each cell, all conflicts for representation could not be fully eliminated. The feature identifier contained in each raster cell was dependent on the order in which the information was converted to the raster image from the vector file. In this conversion process there were two "sequences" to consider. These sequences were the order in which the different classes of features, and the different object types (i.e., points, lines, and polygons), should be converted. If multiple feature identifiers were assigned to the same cell only the number corresponding to the last one would be retained. A hierarchy of importance was developed to define these sequences such that the features deemed most important to the flood simulation and multi-criteria decision making would be converted from vector to raster last. This would ensure that the most important features would not be lost in the conversion. The researcher also decided that the order of conversion of object type for all classes would be points first, then lines, and finally polygons. The order in which the classes were converted is as follows: Trees, Hydroline, Marsh, Lake/Dugout, Rail, Parks/Recreation, Road, Bridge, Industrial Buildings, Municipal Buildings, Residential Buildings, Floodway/Canal, Dyke/Dam, and River.

Once the process had been defined, feature images were produced for each of the twenty-eight tiles. Once produced, the feature images for each tile were assembled along the Red River. The Red River, which is the geographic focus of the analysis in the case study, meanders substantially. For a given tile the river often wandered on and off the feature image. In order to facilitate the analyses the images were assembled in a manner such that the entire river remained on the image at all times. Typically this first involved the assembly of two or three tiles perpendicular to the flow direction of the river. This combination of images was then edited using windowing techniques such that river was relatively centered on the feature image with an approximate minimum distance of 5 km on either side. Figure 4 in Chapter 3 of this thesis is an example of one of the feature maps developed for the data set.

A.2 DIGITAL ELEVATION MODELS (DEMs)

DEMs were required as input for the floodplain analysis model. Their purpose was to identify the ground surface elevation for all locations in the region being modelled. The accuracy with which they represented the exact detailed conditions of the study area was very important. For example, the general trend of the terrain provided by step wise contour maps would be insufficient for the floodplain analysis model. The DEMs must capture the changes in elevation produced by small natural and man-made features such as dykes, roads and ditches. The presence of these small features, which may represent potential paths for or barriers to flood water, had to be accounted for by the floodplain analysis model, when simulating flooding.

DEMs are raster images in which every cell contains an elevation. Unfortunately elevation data was not available at the level of detail required. The elevations of specific features and contour data contained within the DXF files for each tile were available. However this information was insufficient to provide all raster cells in the images representing the entire case study area an elevation value. As a result, a method of completing the elevation surface was required.

There are many methods by which DEMs could be produced. The general approach taken by all methods is to use available elevation data to estimate elevations for regions where there are no data by applying various interpolation routines or other data averaging techniques to the existing information. The difference between the various DEM production methods lies in the interpolation routines used to fill in the missing elevation data. As each method uses a unique interpolation routine, DEMs produced by different approaches, though based on the same data, are often dissimilar. Typically in the creation of the DEM portion of the data set, multiple methods are attempted in order to produce a desirable end product. This process is conducted on a trial and error basis, as each approach is different.

In determining the appropriate method to be used for making the DEMs in this study two main questions were considered. The first was whether the elevation surface produced represented the actual conditions of the area being investigated in sufficient detail. The answer to this question was evaluated by visually inspecting the DEMs produced by the different methods. The second question considered was the amount of time required to produce each elevation image. Because each method uses different interpolation routines to develop DEMs, the time required for their production varied. A short production time was considered an asset.

A.2.1 Preparation of Elevation Data

In addition to their x and y coordinate locations the DXF files also contained data representing elevations of the features within the study area. As was the case with the feature information, the elevations had to be converted from DXF format into a form from which DEMs could be produced. IDRISI modules, however, could not be used to convert the features based on their elevations. As a result, the researcher wrote FORTRAN programs and applied them to the DXF files in order to extract feature elevations. These programs converted the elevations from their DXF format into a vector point file for each tile. From this format the elevation information could be easily prepared for use by all DEM production methods attempted in this study.

Large numbers of point, or spot elevations of the features were obtained from the DXF files with each tile typically containing between 100 000 to 500 000 data points. The elevations themselves as contained within the vector point files were real numbers with one decimal place accuracy. While in vector format these elevations were inspected for obvious errors. There were two main types of errors in the elevation data which required correction. The first involved the elimination of selected data for which the elevation values did not correspond to the ground surface. In processing the three-dimensional aerial photographs used as one of the data sources, the elevation of features such as buildings that were obtained, corresponded to the highest point of the features. Ground surface elevations were needed to produce DEMs. As a result all elevations in the data set not corresponding to the ground surface were eliminated. The second type of error that required correction pertained to elevations with obviously incorrect values. Often the feature elevations contained in the vector files had values which were either negative, or orders of magnitude different from other surrounding features. If a proper elevation for the feature could be estimated the value was corrected, otherwise it was eliminated.

The case study area was located in the low-lying flat terrain of the prairies, and variation in elevation was very small, often less than 1 m. DEMs produced on the basis of elevation data with a small range are often of poor quality. This is because during the data averaging or interpolation process numbers are often rounded off, and in some cases decimal places are lost due to truncation. If the only variation in the elevation data is lost due to rounding the final DEM produced would either appear to have no variation in elevation or the elevation transitions would be very coarse. The potential for this problem was reduced by increasing the range of the data above the decimal place by multiplying all elevation values in the vector point files by a factor of ten.

If possible, DEMs should be produced from elevation data that is evenly distributed for best results. Though large numbers of spot elevations were available for use in producing DEMs they were very localized in most instances. Specific regions, such as communities, were well described with both feature and elevation data, but remote areas such as forested areas and farm land were not. With respect to producing DEMs in some cases, this necessitated the interpolation of large distances in order to determine elevations for regions where there were no available data. Interpolating long distances has a negative effect on both the appearance and accuracy of the DEMs. Problems produced by uneven distribution of source elevation data could be remedied by careful selection of the cell resolution in which the DEMs were to be produced.

When producing DEMs a small grid size would result in a large number of cells containing no information, which would require estimated elevations through interpolation. DEMs produced for the case study required a small cell size of 5 m which when combined with the uneven distribution of the source elevation data would result in the production of poor quality DEMs for the case study. In order to improve the quality of the DEMs it was necessary to try to get a more even distribution of the original data. This was accomplished by increasing the cell size of the DEMs being produced. By doing so, the number of cells requiring estimated elevations would decrease. In this way it was determined through experimentation that the DEMs would be produced at an original cell size of 10 m. After they had been produced the DEMs were then stretched to a cell resolution of 5 m.

In order for both the feature images and DEMs to be used in the analysis not only did they have to have the same cell resolution but both images are also had to represent the exact same geographic location. To satisfy this requirement, the DEMs were produced in image sizes and locations in accordance with the manner that had been used to assemble the feature images as discussed above. Thus in preparation, the point elevations obtained from each tile were sorted and combined into vector files representing the same locations as the arranged feature images and were used to produce DEMs.

A.2.2 DEM Production

A discussion and evaluation of the three methods attempted to produce DEMs follows. A sample vector file containing spot elevations for an individual tile was produced, as described above, and used for experimentation with the three methods.

A.2.2.1 Vector Interpolation

The first method used to produce DEMs was the IDRISI vector interpolation module INTERPOL. This interpolation routine uses a distance weighted average with a six-point search radius about each interpolated point. A quadratic exponent was selected for the weighted average to achieve maximum efficiency by minimizing the time required to calculate the interpolation. The INTERPOL module utilizes a vector file containing point elevations as source information. Though this was available, based on limitations of this module a maximum of 16 000 points per input vector file could be used to produce a DEM. As a result the vector files produced from each tile would require modification. In order to use as much of the available data as possible, the files were quartered, based on their geographic dimensions, and roughly 7 000 randomly selected points per subsection were used. Each quarter of the DEM was produced separately and assembled afterwards. Fewer than the maximum of 16 000 data points were used in order to decrease computation time. Thus approximately 28 000 of a maximum of 64 000 data points per tile were used. With a 10 m cell resolution specified in the output map, total computation time required to produce a DEM for one tile was approximately five days. Visually the DEM appeared smooth and realistic but accuracy was seriously questioned because only a small portion of the available elevation data had been used.

A.2.2.2 Raster Interpolation

The second method used to produce DEMs was the IDRISI raster interpolation module INTERCON. This module uses an eight directional linear interpolation approach, and requires that the source elevations from which it interpolates be contained in a raster image. For this reason spot elevations from the sample tile contained in vector format were first converted to raster. This was accomplished in the same manner in which the feature images had been produced. With respect to the order of conversion of elevations from vector to raster a similar hierarchy of importance was followed as had been used with the features, as discussed above. In contrast to the INTERPOL module there was no restriction on the number of spot elevations that could be used per map. Also in the case of INTERCON the greater the amount of input data, the shorter the computation time required to produce a DEM. Because of this, features with known elevation on the qualitative data maps (e.g., rivers, lakes) were isolated, contracted to a 10 m cell resolution, assigned their elevation value, and added to the raster input map to increase the amount of elevation information. The computation time required to produce a DEM for a complete tile at 10 m resolution using INTERCON was approximately two days. The quality of the elevation surface produced with this method was very poor. The DEM appeared to be a series of "stars" as a result of the eight directional linear interpolation. This obviously inaccurate outcome was very noticeable in areas, such as uninhabited locations, where little spot elevation data had been available. A variety of filters were applied to the image in an attempt to smooth the elevation surface, but little success was attained.

A.2.2.3 Distance-Allocation Method

The final method used to produce DEMs was a multi-stage procedure, suggested by the IDRISI technical support, which required the use of both the DISTANCE and ALLOCATE IDRISI modules. The same raster image containing feature elevations used in the INTERCON method described above was required as input for this procedure. Once again, as more data was used as input, the time required to produce a DEM decreased, and the accuracy of the DEM increased.

Application of the DISTANCE module to the raster elevation input image produced an image containing the minimum Euclidean distance to each empty cell from the nearest source of elevation information. The ALLOCATE module required the DISTANCE output image and the original spot elevation map as input. When applied, this module allocated the elevation values of a given cell from the elevation input image to all of the nearest empty cells, as dictated by the DISTANCE output image for the entire map. Thus each spot elevation from the input data was spread outward, from its corresponding geographic location, across the image until overlap with other data points occurs.

Based on visual inspection, the DEM produced showed the general trend of the ground surface in a flat step-wise fashion. This elevation surface more accurately depicted the flat terrain of the low lying prairie than did the surfaces produced using an interpolation procedure, with the exception of the sudden transitions. These elevation steps were effectively reduced by applying a mean (i.e., low pass) filter to the image. Production of a DEM using this method on a full tile required approximately two hours of computation time.

A.2.3 Method Selection and Implementation

Based on its merits the DISTANCE-ALLOCATE method was selected and used for DEM production for the case study. Visual inspection confirmed that the DEMs produced using this method were the most detailed and realistic and yet still appeared smooth. Known features such as built-up areas and ring dikes were apparent in the final image. This was not so using the other two methods. Using statistical comparison, DEMs produced by all three methods had the same mean elevation and standard deviation. Thus this information could not be used to assist in the method selection. In contrast to INTERPOL, INTERCON and the DISTANCE - ALLOCATE methods use all of the available data. Given this and the five day computation time required using INTERPOL elimination of the DEM produced using this method was easily justified. The DEM produced using INTERCON was eliminated using visual inspection. Though this method used the same input as that of the DISTANCE - ALLOCATE method, the presence of the "stars" on the final image led to a lack of confidence in its accuracy. Also, as previously discussed, it was felt that an interpolation routine did not realistically capture the flatness of low-lying prairies. Finally, of the three DEM production routines, the selected DISTANCE - ALLOCATE method required the least time for computation.

Having identified the appropriate method, DEMs which corresponded to the assembled feature images were produced. Once completed the DEMs still had to be converted from a cell resolution of 10 to 5 m. The pixel duplication option of the EXPAND module was selected to perform this task. Pixel duplication was selected as opposed to a weighted interpolation method, or rubber-sheeting, in order to maintain the "flat" aspect of the DISTANCE - ALLOCATE method. Finally in order to recapture the detail that had been lost in eliminating over-sampling and filtering, the DEMs were updated using POINTRAS, with the original spot elevation data at the new 5 m resolution. In this way small features of significant importance such as dykes, would be accurately described. Shown in Figure 5 in the main document is a sample DEM produced using the Distance-Allocate method. This image shows the elevation data for the feature image in Figure 4 in the main document.

APPENDIX B: FILE CONVERSION PROCEDURES

STEPS TO CONVERT DXF DATA

FEATURES

1. Run DXFIDRIS extracting features based on their name. If "name" does not work try "z-value" or "color" they sometimes produce the same results. Process both polylines and lines if they exist. This module converts the DXF file into a vector file (.VEC), a documentation file (.DVC) and a vector values file (.DVL).

2. Use initial to create a blank background image (use a 5m resolution) with the appropriate coordinates, rows, columns and image type. For features, try to store data as byte binary format as this is very efficient. Use LINERAS to cover the blank image with the vector file just as a check to see that the file converted properly. You can then recreate the blank image.

3. If vector file is ok it must be converted into polygons using TOSCA. The first thing that will likely have to be done is convert the vector file from ASCII to BINARY. First decide which features are relevant (water, multiple classes of buildings, forests, roads, bridges, dykes, ponds, etc.). Use VECTEDIT to isolate specific feature classes as separate files. Remove all garbage from the files but don't be too hasty about getting rid of river line segments that are not convertible to polygons. Label the left and right polygon information for all features in all files and snap the nodes. Run the CYCLE module on each file separately. Each time you run the CYCLE module for each feature, save the new polygons under the file name POLY and the uncycled information as UNCYCLED. APPEND the POLY file to the original feature file (i.e., water) to overlay the original line information with the new polygon features. You do not need the UNCYCLED file. Once all vector feature files for a given tile have been properly converted to polygons, combine all features into one map (make sure you keep track of the feature identifier numbers) using the APPEND command. Once all features have been combined, save the feature file in three components; points, lines, and polygons.

4. Use the three modules POINTRAS, LINERAS, and POLYRAS to update the previously created blank image with the edited vector files containing the points, lines, and polygons.

ELEVATION

1. ZIP the original DXF file and copy to disk on the PC
2. Transfer to UNIX. When using the MCOPY command using the -tn extension will screw up the file in such a manner that is not detectable by the naked eye. With this extension, if you transfer the DXF file back to the PC from UNIX without doing anything but UNZIPing the file IDRISI will not acknowledge the DXF file structure for some reason. If you are converting the DXF file to a VECTOR point file, as best as I can tell the -tn extension does not cause any problems. Without the -tn extension, the DXF file will have "^M" at the end of each line. If you remove these using find and replace, again it does something to the file such that it screws up on IDRISI. The FORTRAN code that you wrote to convert the DXF file to a VECTOR file will work with or without the added characters at the ends of each line.
3. UNZIP file
4. Run FORTRAN code to extract elevation data and output in the form of a VECTOR point file
5. Check file for stupidity (this may not be possible until using HISTO) and correct
6. ZIP file
7. Transfer to PC
8. UNZIP file
9. Check in Microsoft Word for garbage (If garbage then repeat transfer until ok).

10. Create VECTOR documentation file
11. Create blank background image at 10m resolution (INTEGER BINARY) with coordinated matching the vector file.
12. Overlay point VECTOR file onto image using POINTRAS
13. Check image visually to ensure appropriate and using HISTO for incorrect elevations (if incorrect redo on UNIX).
14. Convert Feature Image for the same location as the elevation data from BYTE-PACKED BINARY to INTEGER BINARY
15. Make sure the coordinates of the Elevation and Feature images are the same
16. Reclass feature image to isolate the Rivers
17. Use CONTRACT to reduce the resolution of the River image from 5m to 10m
18. Use GROUP with diagonals in order to separate the main branch of the Red River
19. RECLASS the main branch to a separate image
20. Assign the main branch of the Red River its appropriate elevation for that location as indicated by the elevations of the river banks shown in the image containing the point Elevations.
21. OVERLAY the River elevation on top of the spot elevations to produce a single image containing all elevation information.
22. Multiply the all elevation information by a factor of 10 (refer to this as "complete elevation image").
23. Run DISTANCE on the complete elevation image in order to determine the shortest distance from each blank cell to the cells with the elevation data.
24. Run ALLOCATE on the image produced in step #23 specifying the complete elevation file as the source file.
25. Filter the image produced in #24 using a mean/low pass filter.
26. EXPAND the image produced in #25 using pixel duplication to a resolution of 5m.
27. Update this image using POINTRAS with the original point elevations.

```
      CHARACTER TEN*2,TWENTY*2,THIRTY*2
      REAL X,Y,Z,ADJUST
      INTEGER ZERO,ZZ
      OPEN(15,FILE='an37.dxf')
      OPEN(20,FILE='out1.vec')
      ZERO=0
:     THIS PROGRAM EXTRACTS ELEVATIONS FROM THE DXF FILES AND PLACES
:     THEM IN A VECTOR POINT FILE.  THIS VECTOR POINT FILE IS THEN USED
:     BY DEM MAKING UTILITIES IN ORDER TO CREATE A SMOOTH ELEVATION
:     SURFACE FOR THE CASE STUDY AREA.  THE PROGRAM ITSELF EXTRACTS THE
:     ELEVATIONS BASED ON THE FEATURE IDENTIFIERS IN THE DXF FILES.
:     THE ONLY FEATURE ELEVATIONS OF WHICH ARE EXTRACTED ARE THOSE
:     WHICH PERTAIN TO THE GROUND SURFACE.  ALSO, ELEVATIONS WHICH ARE
:     OBVIOUSLY INCORRECT ARE REJECTED.  THE PROGRAM AS IT IS WRITTEN
:     ALSO ALLOWS THE EXTRACTION OF ELEVATIONS OF SPECIFIC FEATURES
:     BASED ON THEIR GEOGRAPHIC LOCATION.
      DO 10 I=1,40000000
      READ(15,99) TEN
      IF ((TEN.EQ.'JA').OR.(TEN.EQ.'BA').OR.(TEN.EQ.'BB').OR.
     +(TEN.EQ.'BE').OR.(TEN.EQ.'BF').OR.(TEN.EQ.'BH').OR.
     +(TEN.EQ.'BL').OR.(TEN.EQ.'BQ').OR.(TEN.EQ.'BG').OR.
     +(TEN.EQ.'BJ').OR.(TEN.EQ.'BM').OR.(TEN.EQ.'BN').OR.
     +(TEN.EQ.'BR').OR.(TEN.EQ.'CA').OR.(TEN.EQ.'CB').OR.
     +(TEN.EQ.'CC')) THEN
        READ(15,99) TEN
         GOTO 10
      ENDIF
      IF (TEN.EQ.' 1') THEN
           READ(15,*) X
           READ(15,99) TWENTY
           READ(15,*) Y
           READ(15,99) THIRTY
           READ(15,*) Z
      IF (Z.GE.1000) THEN
          ADJUST=Z/10.0
          Z=ADJUST
      ENDIF
      IF ((Z.GT.150).AND.(TWENTY.EQ.' 2').AND.(THIRTY.EQ.' 3')
     +.AND.(X.GE.636000).AND.(Z.LE.300)) THEN
              Z=Z*10
              ZZ=INT(Z)
              WRITE(20,*) ZZ,' 1'
              WRITE(20,100) X,Y
           ENDIF
      ENDIF
      IF ((TEN.EQ.'EO').OR.(TWENTY.EQ.'EO').OR.
     +(THIRTY.EQ.'EO')) THEN
         GOTO 15
      ENDIF
0     CONTINUE
15     CONTINUE
5     WRITE(20,*) ZERO,ZERO
9       format(a2)
00    FORMAT(F12.2,' ',F12.2)
      END
1234567890123456789012345678901234567890123456789012345678901234567890
```

APPENDIX C: GIS MACROS AND EXTERNAL PROGRAMS

The following is a list of GIS macros and external FORTRAN programs used in the floodplain analysis of the Red River Valley. Contained in each of the macros are individual GIS commands which must be executed in the order in which they are listed. For explanation of the commands refer to the IDRISI on-line help menus and Technical Reference Guide. Following most of the commands listed below is a brief description of the functional purpose of each command.

In order to generate the flood protection alternatives the user must change the characteristics of the region of interest as they are represented within the HEC-2 input file as well as the DEM and feature images. These changes are to be done by the user before implementation of the macros listed below.

The first five macros listed below (FLOOD1, DAM1, DAM2, DAM3, and TOTDAM) must be executed for each of the flood protection alternatives. These macros contain the necessary commands to simulate flooding and calculate flood water impacts for each of the flood protection alternatives.

The remaining macros require only a single execution. These macros are responsible for application of the Spatial Compromise Programming approach for the purpose of evaluating the alternatives. These macros have been set up specifically to evaluate four alternatives and three criteria. If there are a different number of alternatives or criteria, changes to these macros should be made.

WARNING: The macros should not be implemented blindly! The lists of commands shown below should only be used as guidance for the user until familiar with a GIS environment. Implementation of these macros in the case study often resulted in unexplanable errors due to difficulties with the software. It is necessary to check the results produced by each of the commands listed below in order to determine if an error has occurred.

MACRO: FLOOD1

This macro was used to determine the spatial extents of the flood waters resulting from implementation of the various flood protection alternatives. Also the flood water depth and benefit of flooding upstream areas criterion are also determined at this time.

assign x reach fldelev reach
Assign water surface elevations to each reach in the reach image
overlay x 2 fldelev dem2 diff
Subtract the ground surface elevation as contained in the DEM from the water surface elevation. The determines the depth of submergence.
reclass x i diff bool 2 1 0 9999 0 -5000 0 -9999
Create a boolean mask of locations having a ground elevation less than the water surface elevation
group x bool n group1
Find all contiguous groups in the mask
extract x rlvloc group1 1 1 grpnum
Select the flooded group based on the location of the main stem of the Red River
call c:\users\rob\bob.exe
Create a values file containing the flooded group identifier
assign x group1 flood1 assign 1
Create an image of just the flooded group
overlay x 7 feat flood1 feat2
Overlay the flooded group under the feature image. "feat2" is just for observational purposes
delete x bool.*
convert x flood1 flood1 i 3 2 2

Convert the flood boolean mask to byte binary file type
delete x group1.*
reclass x i feat river 2 0 2 20 -9999
Create boolean image of the Red River and its tributaries
overlay x 2 flood1 river temp
Subtract river boolean from flood boolean mask
reclass x i temp fldarea 2 0 -5000 0 -9999
Eliminate any negative numbers from rounding in the flooded area mask
overlay x 3 fldarea diff depth
Multiply flooded area mask with depth of submergence to get the "flood water depth" criteria
overlay x 3 depth reach benefit
Multiple "depth" criteria by reach image in order to determine the "benefit of flooding upstream areas" criteria.
delete x temp.*
delete x flood1.*
delete x river.*
delete x diff.*

MACRO: DAM1

This macro determines the percent damages to industrial building produced through the implemented alternative.

reclass x i feat bldg1 2 0 0 9 1 9 10 0 10 20 -9999
Create boolean mask of industrial buildings
overlay x 3 fldarea bldg1 subbldg1
Multiply flooded area mask with industrial building mask. This identifies the potentially submerged buildings, or buildings having a ground elevation less than the water surface elevation.
delete x bldg1.*
overlay x 3 subbldg1 dem2 elev1
Multiply the potentially submerged buildings by the DEM. This produces the image elev1 which contains the ground elevations of the potentially submerged buildings.
overlay x 2 fldelev elev1 depth
Subtract the building elevations from the flood water surface elevation. This identifies the depth of flooding in each of the potentially submerged buildings.
delete x elev1.*
group x subbldg1 y bldggrp
This determined the number of potentially submerged buildings. Each potentially submerged building is given a unique identifier in the image bldggrp.
extract x bldggrp depth 1 1 depth
This extracts the flooded depths of the potentially submerged buildings and places them in a values file with the corresponding building identifier.
call c:\users\rob\damage.pif
Apply stage-damage curve. If the potentially submerged building is flooded to a depth less than the available flood proofing, the building receives no damage.
assign x bldggrp damage1 damage
Assign the % damages to each of the submerged buildings. Each cell corresponding to the location of the building contains the % damage of the whole building.
delete x subbldg1.*

MACRO: DAM2

This macro does the same as the above DAM1 except that it is for the municipal buildings. For a detailed description of the individual commands refer to macro DAM1.

reclass x i feat bldg2 2 0 0 10 1 10 11 0 11 20 -9999
overlay x 3 fldarea bldg2 subbldg2
delete x bldg2.*
overlay x 3 subbldg2 dem2 elev2
overlay x 2 fldelev elev2 depth
delete x elev2.*
group x subbldg2 y bldggrp
extract x bldggrp depth 1 1 depth
call c:\users\rob\damage.pif
assign x bldggrp damage2 damage
delete x subbldg2.*

MACRO: DAM3

This macro does the same as the above DAM1 except that it is for the residential buildings. For a detailed description of the individual commands refer to macro DAM1.

reclass x i feat bldg3 2 0 0 11 1 11 12 0 12 20 -9999
overlay x 3 fldarea bldg3 subbldg3
delete x bldg3.*
overlay x 3 subbldg3 dem2 elev3
overlay x 2 fldelev elev3 depth
delete x elev3.*
group x subbldg3 y bldggrp
extract x bldggrp depth 1 1 depth
call c:\users\rob\damage.pif
assign x bldggrp damage3 damage
delete x subbldg3.*
delete x bldggrp.*

MACRO: TOTDAM

This macro calculates the total dollar value of building damages. Damages to all three classes of buildings are combined onto a single image. Also each of the criteria images are stored separately into new images for each alternative in preparation for evaluation.

scalar x damage1 dollar1 3 2000
Multiply the image containing the % damage to industrial buildings by their value of $200 000. This produces an image in which each cell of the damaged industrial buildings contains the $ value of damage to the whole building.
scalar x damage2 dollar2 3 1000
Multiply the image containing the % damage to municipal buildings by their value of $100 000. This produces an image in which each cell of the damaged municipal buildings contains the $ value of damage to the whole building.
scalar x damage3 dollar3 3 500
Multiply the image containing the % damage to residential buildings by their value of $50 000. This produces an image in which each cell of the damaged residential buildings contains the $ value of damage to the whole building.

overlay x 7 dollar3 dollar2 temp
Combine the damages of municipal and residential buildings onto one image.
delete x dollar3.*
delete x dollar2.*
overlay x 7 temp dollar1 totdam
Combine industrial building damages with the municipal and residential damages.
delete x temp.*
delete x dollar1.*
group x totdam y bldggrp
This identifies the total number of flooded buildings. The image bldggrp shows each flooded building with a unique identifier.
area x bldggrp 1 1 bldgarea
This finds the number of cells composing each building. The the locations/cells of the damaged buildings contain the number of cell which compose each of the flooded buildings.
overlay x 4 totdam bldgarea bldgdam
By dividing the damages to the whole building by the buildings' area this produces an image in which each cell contains the $ value of damage for each individual building cell.

INTERMEDIATE FIXUPS!

Having completed the determination of the three selected flood water impacts for each alternative, the alternatives could be evaluated. A separate image containing the criteria values for each alternative would be produced by this stage through implementation of the above macros. The images in which the criteria values for each alternative are contained are named as follows:

a1c1- alternative 1, criteria 1
a1c2- alternative 1, criteria 2
a1c3- alternative 1, criteria 3
a2c1- alternative 2, criteria 1
a2c2- alternative 2, criteria 2
a2c3- alternative 2, criteria 3
a3c1- alternative 3, criteria 1
a3c2- alternative 3, criteria 2
a3c3- alternative 3, criteria 3
a4c1- alternative 4, criteria 1
a4c2- alternative 4, criteria 2
a4c3- alternative 4, criteria 3

IMPORTANT NOTE

In these images the criteria as they are numbered here is different from within the text of the thesis. Please don't ask why! The criteria number for the purpose of the GIS commands and file names are as follows:

criteria 1:building damage
criteria 2:flood water depth
criteria 3:benefit of flooding upsteam areas

Having produces the above listed images, additional images showing the best and worst criteria values for each location can be created for use by the Spatial Compromise Programming approach. For the three criteria the following logic was used in the development of the optimal and worst criteria images.

Building damage criteria:

optimal=minimum cell value for each location
worst=maximum cell value for each location

Flooded depth criteria:

optimal=minimum cell value for each location
worst=maximum cell value for each location

Benefit of flooding upstream areas criteria:

worst=minimum cell value for each location
optimal=maximum cell value for each location

MACRO: COMPRO1

reclass x i worst1 temp1 2 1 0 1 0 1 500000 -9999

For all locations which do not contain a flooded building assign a value of 1. All locations where there are is a flooded building receive a value of zero. These values are contained in the image temp1. This step was necessary in order to prevent the occurance of the ratio of 0/0 in the computation of the distance metrics.

overlay x 7 worst1 temp1 den1

Cover the image containing the worst criteria values with temp1. The result of this operation produced the denominator of the distance metric equation for criteria 1(den1). This operation was necessary because some building locations had a worst criteria value of zero. If the zero remained in the image the ratio of the numerator/denomintor of the distance metric equation could still result in 0/0. This had to be avoided in the GIS otherwise inaccurate results of the analysis would occur.

overlay x 2 worst1 a1c1 num1

Compute numerator (num1) of modified distance metric equation for alternative 1, criteria 1 by subtracting the actual criteria 1 values (a1c1) from the worst possible value (worst 1) between the alternatives for each location.

overlay x 4 num1 den1 temp2

Divide the numerator (num1) of the equation by the denominator (den1). The image produced through this (temp2) represents the portion of the distance metric equation within the absolute value brackets.

scalar x temp2 temp3 5 0.5

Apply the 1/p exponent to temp2 to produce temp3

scalar x temp3 part1 3 0.25

Multiply each cell in the temp3 image by the value of w_i^p which equals to 0.25

delete x temp1.*

delete x temp2.*

delete x temp3.*

delete x num1.*

reclass x i worst2 temp1 2 1 0 1 0 1 32000 -9999

For all locations which were not flooded assign a value of 1. All locations which were flooded receive a value of zero. These values are contained in the image temp1. This step was necessary in order to prevent the occurance of the ratio of 0/0 in the computation of the distance metrics.

overlay x 7 worst2 temp1 den2

Cover the image containing the worst criteria values with temp1. The result of this operation produced the denominator of the distance metric equation for criteria 2 (den2). This operation was necessary because some building locations had a worst criteria value of zero. If the zero remained in the image the ratio of the numerator/denomintor of the distance metric equation could still result in 0/0. This had to be avoided in the GIS otherwise inaccurate results of the analysis would occur.

overlay x 2 worst2 a1c2 num2

Compute numerator (num2) of modified distance metric equation for alternative 1, criteria 2 by subtracting the actual criteria 2 values (a1c2) from the worst possible value (worst 2) between the alternatives for each location.
overlay x 4 num2 den2 temp2
Divide the numerator (num2) of the equation by the denominator (den2). The image produced through this (temp2) represents the portion of the distance metric equation within the absolute value brackets.
scalar x temp2 temp3 5 0.5
Apply the 1/p exponent to temp2 to produce temp3
scalar x temp3 part2 3 0.0625
Multiply each cell in the temp3 image by the value of w_i^p which equals to 0.0625
delete x temp1.*
delete x temp2.*
delete x temp3.*
delete x num2.*
reclass x i best3 temp1 2 1 0 1 0 1 100000 -9999
For all locations which were not flooded assign a value of 1. All locations which were flooded receive a value of zero. These values are contained in the image temp1. This step was necessary in order to prevent the occurance of the ratio of 0/0 in the computation of the distance metrics.
overlay x 7 best3 temp1 den3
Cover the image containing the best criteria values with temp1. The result of this operation produced the denominator of the distance metric equation for criteria 3 (den3). This operation was necessary because some building locations had a worst criteria value of zero. If the zero remained in the image the ratio of the numerator/denomintor of the distance metric equation could still result in 0/0. This had to be avoided in the GIS otherwise inaccurate results of the analysis would occur.
overlay x 4 a1c3 den3 temp2
Divide the numerator (a1c3) of the equation by the denominator (den3). The numerator in this case was simply the criteria values themselves. This was because the worst value for this criteria was zero. The image produced through this (temp2) represents the portion of the distance metric equation within the absolute value brackets.
scalar x temp2 temp3 5 0.5
Apply the 1/p exponent to temp2 to produce temp3
scalar x temp3 part3 3 0.0625
Multiply each cell in the temp3 image by the value of w_i^p which equals to 0.0625
delete x temp1.*
delete x temp2.*
delete x temp3.*
overlay x 1 part1 part2 temp1
Add the contributions to the distance metric values from criteria one and two.
overlay x 1 temp1 part3 sum1
Add the contribution to the distance metric from criteria three.
scalar x sum1 l1 5 2
Apply the exponent p to the summed components of the distance metric. This produced the final image l1 which contained the distance metric values for alternative 1.

MACRO: COMPRO2

The purpose of this macro was to compute the distance metric for each location in the region of interest for alternative 2. As the commands required to do so are the same as those for the first alternative, explanation of the contents of this macro can be found in COMPRO1.

overlay x 2 worst1 a2c1 num1

```
overlay x 4 num1 den1 temp2
scalar x temp2 temp3 5 0.5
scalar x temp3 part1 3 0.25
delete x temp2.*
delete x temp3.*
delete x num1.*
overlay x 2 worst2 a2c2 num2
overlay x 4 num2 den2 temp2
scalar x temp2 temp3 5 0.5
scalar x temp3 part2 3 0.0625
delete x temp2.*
delete x temp3.*
delete x num2.*
overlay x 4 a2c3 den3 temp2
scalar x temp2 temp3 5 0.5
scalar x temp3 part3 3 0.0625
delete x temp2.*
delete x temp3.*
overlay x 1 part1 part2 temp1
overlay x 1 temp1 part3 sum2
scalar x sum2 l2 5 2
```

MACRO: COMPRO3

The purpose of this macro was to compute the distance metric for each location in the region of interest for alternative 3. As the commands required to do so are the same as those for the first alternative, explanation of the contents of this macro can be found in COMPRO1.

```
overlay x 2 worst1 a3c1 num1
overlay x 4 num1 den1 temp2
scalar x temp2 temp3 5 0.5
scalar x temp3 part1 3 0.25
delete x temp2.*
delete x temp3.*
delete x num1.*
overlay x 2 worst2 a3c2 num2
overlay x 4 num2 den2 temp2
scalar x temp2 temp3 5 0.5
scalar x temp3 part2 3 0.0625
delete x temp2.*
delete x temp3.*
delete x num2.*
overlay x 4 a3c3 den3 temp2
scalar x temp2 temp3 5 0.5
scalar x temp3 part3 3 0.0625
delete x temp2.*
delete x temp3.*
overlay x 1 part1 part2 temp1
overlay x 1 temp1 part3 sum3
scalar x sum3 l3 5 2
```

MACRO: COMPRO4

The purpose of this macro was to compute the distance metric for each location in the region of interest for alternative 4. As the commands required to do so are the same as those for the first alternative, explanation of the contents of this macro can be found in COMPRO1.

```
overlay x 2 worst1 a4c1 num1
overlay x 4 num1 den1 temp2
scalar x temp2 temp3 5 0.5
scalar x temp3 part1 3 0.25
delete x temp2.*
delete x temp3.*
delete x num1.*
overlay x 2 worst2 a4c2 num2
overlay x 4 num2 den2 temp2
scalar x temp2 temp3 5 0.5
scalar x temp3 part2 3 0.0625
delete x temp2.*
delete x temp3.*
delete x num2.*
overlay x 4 a4c3 den3 temp2
scalar x temp2 temp3 5 0.5
scalar x temp3 part3 3 0.0625
delete x temp2.*
delete x temp3.*
overlay x 1 part1 part2 temp1
overlay x 1 temp1 part3 sum4
scalar x sum4 l4 5 2
```

MACRO: FIXUP

Before the distance metric images for each alternative could be compared, the values had to be scaled to an appropriate magnitude. Also the image file types had to be converted. These were requirements of the IDRISI module MDCHOICE which was used to rank the alternatives.

The numbers which could be compared by the module MDCHOICE had to be within the range of 0 to 255. It was found that by multiplying the distance metric images by a value of 1000 this range in the numbers could be attained. These operations are shown in the first four scalar commands listed below. The next four commands convert the distance metric images to byte binary format. This file format is also required by the module MDCHOICE.

```
scalar x l1 temp1 3 1000
scalar x l2 temp2 3 1000
scalar x l3 temp3 3 1000
scalar x l4 temp4 3 1000
convert x temp1 final1 i 3 2
convert x temp2 final2 i 3 2
convert x temp3 final3 i 3 2
convert x temp4 final4 i 3 2
delete x temp1.*
delete x temp2.*
delete x temp3.*
delete x temp4.*
```

Finally the GIS module MDCHOICE was applied to the distance metric images in order to rank the alternatives.

MDCHOICE x 4 ranked 255 final1 0.25 0 final2 0.25 0 final3 0.25 0 final4 0.25 0

This command produced an image in which each cell contained the number of the best alternative for that location. If a tie occurred between the alternative, the one which was listed first in the command line as shown above would win. Thus multiple ranking orders were attempted for each weight set to identify those locations in which ties occurred.

EXTERNAL FORTRAN PROGRAMS

PROGRAM: BOB.FOR

```
c This program was used by the macro FLOOD1 to identify and select the flooded group
c identifier value. This value was then placed in a separate file for further use by the
c macro

 INTEGER ZERO1,ZERO2,ONE,NUMBER
    OPEN(15,file='c:\users\rob\analysis\GRPNUM.VAL')
    OPEN(20,file='c:\users\rob\analysis\ASSIGN.VAL')
    READ(15,*) ZERO1,ZERO2
    READ(15,*) ONE,NUMBER
    WRITE(20,*) ZERO1,ZERO2
    WRITE(20,*) NUMBER,ONE
    CLOSE(15)
    CLOSE(20)
    END
```

PROGRAM: DAMAGE.FOR

```
c  This program applies the stage-damage relationship to the flooded buildings.
c  Input to the program are the identifiers and depths of submergence for all potentially
c  flooded buildings. In this program the effects of flood warning and flood proofing could
c  be accounted for as shown below.

    REAL DEPTH,TEMP
    INTEGER NUMBER,DAMAGE
    OPEN(10,FILE='C:\USERS\ROB\analysis\DEPTH.VAL')
    OPEN(15,FILE='C:\USERS\ROB\analysis\DAMAGE.VAL')
5    READ(10,*,END=50) NUMBER,DEPTH
    IF((DEPTH.GE.1000).OR.(DEPTH.LE.0)) THEN
        TEMP=0.0
        GOTO 6
    ENDIF
      DEPTH=DEPTH/10
      IF(DEPTH.GE.(2.9)) THEN
c  if the flood water depth was greater than 2.9 m the building was considered
c  to be destroyed. The value of 2.9 m was selected based on the information
c  obtained from the ECOS study.
        TEMP=100.0
        GOTO 6
```

```
      ENDIF
C       IF(DEPTH.LE.(1.0)) THEN
c  the effects of flood proofing can be accounted for in this portion of the program
C          TEMP=0.0
C          GOTO 6
C       ENDIF
      TEMP=17.529-22.829*DEPTH+45.894*DEPTH**2-9.301*DEPTH**3
c  no flood warning stage damage curve
C     TEMP=7.529-22.829*DEPTH+45.894*DEPTH**2-9.301*DEPTH**3
c  normal stage damage curve
6     DAMAGE=INT(TEMP)
      WRITE(15,100) NUMBER,DAMAGE
100   FORMAT(I6,I6)
      GOTO 5
50    CLOSE(UNIT=10)
      CLOSE(UNIT=15)
      END
```