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A Spatial Fuzzy Compromise Approach for Flood Disaster Management

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VERITAS ET UTILITAS

A SPATIAL FUZZY COMPROMISE APPROACH FOR FLOOD DISASTER MANAGEMENT

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EXECUTIVE SUMMARY

Natural disasters affect regions with different intensity and produce damages that vary in space. Topographical features of the region; location of properties that may be exposed to the peril; level of exposure; impact of different mitigation measures; are all variables with considerable spatial variability. A new method for evaluation of disaster impacts has been presented in this report that takes into consideration spatial variability of variables involved and associated uncertainty. Flood management has been used to illustrate the utility of proposed approach.

Floodplain management is a spatial problem. Representation of flood damage mitigation alternatives and objectives in space provides a better insight into the management problem and its characteristics. Protection of a region from floods can be achieved through various structural and non-structural measures. Comparison of different measures and evaluation of their impacts is based on the multiple criteria. If they are described spatially, decision-making problem can be conceptualized as spatial multi criteria decision-making (MCDM). Tkach and Simonovic (1997) introduced spatial Compromise Programming (SPC) technique to account for spatial variability in flood management.

Some of the criteria and preferences of the stakeholders involved with flood management are subject to uncertainty that may originate in the data, knowledge of the domain or our ability to adequately describe the decision problem. The main characteristic of flood management is the existence of objective and subjective uncertainty. Fuzzy set theory has been successfully used to address both, objective and subjective uncertainty. Bender and Simonovic (2000) incorporated vagueness and imprecision as sources of uncertainty into multi criteria decision-making in water resources.

In this report a new technique named Spatial Fuzzy Compromise Programming (SFCP) has been developed to enhance our ability to address the issues related to uncertainties in spatial environment. A general fuzzy compromise programming technique, when made

spatially distributed, proved to be a powerful and flexible addition to the list of techniques available for decision making where multiple criteria are used to judge multiple alternatives. All uncertain variables (subjective and objective) are modeled by way of fuzzy sets. In the present study, fuzzy measures have been introduced to spatial multi criteria decision-making in the GIS environment in order to account for uncertainties.

Through a case study of the Red River floodplain near the City of St. Adolphe in Manitoba, Canada, it has been illustrated that the new technique provides measurable improvement in flood management. Final results in the form of maps that shown spatial distribution of the impacts of mitigation measures on the region can be of great value to insurance industry.

Keywords: Water resources, flood management, disaster mitigation, spatial compromise programming, multi-criteria decision making, spatial fuzzy multi objective analysis.

INTRODUCTION

"The nature of floods and their impact depend on both natural and human-made conditions in the floodplain. Economic development and the installation of flood protection measures have political, economic, and social dimensions as well as engineering aspects. Hydrologic and hydraulic analysis of floods provides a sound technical basis for management decision making that must weigh numerous other factors" (Hoggan, 1997). Recent flood management is emphasizing a more integrated approach including measures such as source control (watershed/landscape structure management), insurance, forecasting, warning and land use planning (Simonovic, 2002; Kundzewicz, 2002).

Selecting the best strategy from a number of potential alternatives in water resources planning and management is a complicated decision making process (Bose and Bose, 1995). Compromise programming (Zeleny, 1973), a multi criteria decision making (MCDM) technique, is a powerful tool in assisting floodplain management in general. Conventionally, most of the planning is done without considering spatial heterogeneity and uncertainty involved with such complex processes.

Applications of MCDM techniques to water resources have come a long way since the work of Maass et al. (1962) and Cohon and Marks (1973), where the decision problems were formulated as linear programming vector optimization problems. There also exist methodologies based on multiattribute utility theory based on the work of Raiffa (1968), where explicit trade-offs between attributes are utilized. Other popular techniques used for discrete alternative selection include the Surrogate Worth Trade Off (Haimes 1998), ELECTRE (Roy 1971), Analytical Hierarchy Process (Saaty 1980), and Compromise Programming (CP). PROTRADE method (Goicoechea et al. 1982) included for the first time the uncertainties into the MCDM. Traditionally, the uncertainty arising from vagueness and imprecision is addressed in MCDM mostly through sensitivity analysis. However, only subjective uncertainty can be evaluated by sensitivity analysis, which can be inadequate at expressing both the probabilistic and imprecise forms of uncertainty.

Typical flood management problem requires selection and implementation of the best solution from the set of potential alternatives. Flood management problems, in general, may include conflicting quantitative and qualitative criteria and multiple decision-makers. MCDM techniques help in evaluation and ranking of alternatives based on the criteria values associated with each of the alternatives, and preferences of the various decision makers. However, the flood management alternatives exhibit spatial variability. Geographic Information System (GIS) is a useful tool to assist in water resources planning with spatially distributed variables (flood management in this particular study). "Specific planning and management tasks for which GIS 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 action (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). Many GIS applications in water resources decision making include work of different research groups (McKinney and Maidment, 1993; Carver, 1991; Pereira and Duckstein, 1993; Banai, 1993; Tim, 1997; and Wolfe, 1997). GIS technology facilitates the decision making process based on its analytical capabilities with spatial information. In addition to this, many of the GIS systems are equipped with a graphical user interface, which increases the decision maker's comprehension of the spatial information that is involved in the problem being addressed. Based on these two potential additions to the decision making process, a GIS is often included as a major component in the development of Decision Support Systems (DSS) (Simonovic, 1993, 1998; Walsh, 1993; Fürst el. al., 1993; Leipnik et. al., 1993; Watkins et. al., 1996; and Fedra, 1997).

Conventional MCDM techniques 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 the best for an entire region by a conventional MCDM may not be the best for all locations within that region. Tkach and Simonovic (1997) addressed this spatial variability in the criteria values associated with the various alternatives by combining the CP with the GIS technology and called it Spatial Compromise Programming (SCP). SCP can be efficiently used to generate, evaluate, and rank a set of potential flood protection alternatives. Through the application of the CP technique the best alternative can be determined for the entire region. However, with the SCP, rather than determining a single value per alternative, a distance metric is calculated for each impacted location for each alternative. The best alternative for each location within the region is determined using SCP. Though SCP is capable of accounting for the spatial variability factor, it is unable to address various uncertainties associated with complex system of multiple alternatives, multiple criteria and multiple decision makers. Uncertainties in model assumptions, data, or parameter values, also contribute to the complexity in decision making process.

MCDM has been moving from optimization methods to more interactive decision tools (Bender and Simonovic, 2000). Some of the areas of current and future development in the field have been identified by Dyer et. al. (1992). One of them being "Sensitivity analysis and the incorporation of vague or imprecise judgments of preferences and/or probabilities in multi-attribute situations and decisions under uncertainty in which states are multidimensional." Traditional techniques for evaluating discrete alternatives such as ELECTRE (Benayoun et. al., 1966), AHP (Saaty, 1980), Compromise Programming (Zeleny, 1973; Zeleny, 1982), and other do not normally consider uncertainties involved in procuring criteria values. Sensitivity analysis can be used to express decision maker uncertainty (such as uncertain preferences and ignorance), but this form of sensitivity analysis can be inadequate at expressing decision complexity. There have been efforts to extend traditional techniques, such as PROTRADE (Goicoechea et. al., 1982), which could be described as stochastic compromise programming technique. The problem, though, is that not all uncertainties fit the probabilistic classification. The theory of fuzzy sets, which is a theory of possibility, is not dissimilar to probability theory. In fact, they can be considered complementary. Fuzzy membership functions have a similar appearance to probability distribution functions. However, there are some inherent differences. A probability distribution function provides the probability of specific values occurring. A fuzzy membership function acknowledges that we may not be completely sure what values are being talked about. Statistical precision can be independent of our classification of an event. In many cases, there may not be enough data to make probabilistic predictions with confidence. The dependence of stochastic applications on distribution functions can be restricting and misleading because of the intensity of data requirements. The difference between fuzzy and probabilistic functions is not always so clear. A fuzzy membership function may be used in place of a probability density function, but the same data requirements are still relevant. In general, fuzzy sets provide an intuitive, and flexible framework for interactively exploring a problem that is either ill defined or has limited available data.

Fuzzy decision making techniques have addressed some uncertainties, such as the vagueness and conflict of preferences common in group decision making (Blin, 1974; Siskos, 1982; Seo and Sakawa, 1985; Felix, 1994; and others), and at least one effort has been made to combine decision problems with both stochastic and fuzzy components (Munda et. al., 1995). Application, however, demands some level of intuitiveness for the decision makers, and encourages interaction or experimentation such as that found in Nishizaki and Seo (1994). Authors such as Leung (1982) and many others have explored fuzzy decision making environments. Fuzzy decision making process is not always intuitive to all people involved in practical decisions because the decision space may be some abstract measure of fuzziness, instead of a tangible measure of alternative performance. The alternatives to be evaluated are rarely fuzzy. Their performance is fuzzy. In other words, a fuzzy decision making environment may not be as generically relevant as a fuzzy evaluation of a decision making problem. The Fuzzy Compromise Programming (FCP) technique developed by Bender and Simonovic (2000) transforms a distance metric to a fuzzy set by changing all inputs from crisp to fuzzy applying fuzzy extension principle. This approach can address various uncertainties that are associated with the natural hydrological processes occurring in flood management; data monitoring systems; equipment accuracy; and lack of knowledge. FCP approach ranks alternatives using fuzzy ranking measures designed to capture the effect of risk tolerance differences among decision makers.

In flood management time and space play important role, therefore, there are uncertainties involved in flood prediction; in evaluation of the inundated area; and in estimation of various physical, ecologic, economic and social impacts. Considering the literature available on MCDM techniques, such as, CP, SCP, fuzzy compromise programming and GIS, it has been realized that there is a need to develop a methodology that combines the two important issues; (i) accounting for spatial variability in decision making, and (ii) accounting for uncertainties involved in decision making. A new technique combining these two objectives has been developed in this study, which will be called herein as Spatial Fuzzy Compromise Programming (SFCP). Through a case study of the Red River Basin, Manitoba, Canada it has been successfully demonstrated that SFCP can, using a GIS environment, assist a decision maker in selecting the best flood protection alternative, taking into account the spatial variability (using SCP), for each location (5 x 5 m grid) in the entire study region as well as accounting for the uncertainties (using Fuzzy Compromise Programming) involved in the process.

In the following sections, development of proposed Spatial Fuzzy Compromise Programming methodology has been explained. This section starts with the description and formulation of the flood management problem under uncertainty with spatially variable criteria. Detailed presentation of the solution methodology follows with the emphasis on the use of fuzzy set theory. Section 3 presents a case study of the Red River Basin flood protection strategy with the description of existing flood protection system and the solution of deterministic and fuzzy problem formulations. Discussion of the results has been presented as well. Conclusions derived from this study are discussed in Section 4.

1. SPATIAL FUZZY MULTI OBJECTIVE ANALYSIS

General formulation of a multi-objective multiple-participant decision problem is based on the following basic components: (a) A set of potential alternatives; (b) A set of objectives or criteria; (c) A number of decision makers; (d) A preference structure or weights; and (e) A set of performance evaluations of alternatives for each objective or criteria.

A multi-objective problem is characterized by a *p*-dimensional vector of objective functions. In mathematical terms, this can be formulated as:

$$Z(x) = [Z_1(x), Z_2(x), ..., Z_p(x)] \quad (1)$$

subject to

$$x \in X \quad (2)$$

where X is a feasible region defined as:

$$X = \{x : x \in R^n, g_i(x) \leq 0, x_j \geq 0 \forall i, j\} \quad (3)$$

where R = set of real numbers; $g_i(x)$ = set of constraints; and x = set of decision variables.

Every feasible solution to the problem (Eq.(1)), i.e. all $x \in X$, implies a value for each objective, i.e., $Z_k(x)$, $k = 1, \ldots p$. The p-dimensional objective function maps the feasible region in decision space X into the feasible region in objective space $Z(x)$, defined on the p-dimensional vector space.

In general, one cannot optimize a vector of objective functions (Haimes and Hall, 1974). In order to find an optimal solution, it is required that information about preferences are available. Without this information the objectives are incommensurable and therefore incomparable implying that optimum solution could not be achieved since all feasible solutions are not ordered (comparable). A complete ordering can be obtained in this case only by introducing value judgments into the decision making process.

In the first step of the multi-objective analysis problem, a set of nondominated or 'noninferior' solutions is sought within the feasible region instead of seeking a single optimal solution. The nondominated solutions are the conceptual equivalents in multi-objective problems to a single optimal solution in a single-objective problem. For each of the solutions outside the nondominated set, there is a nondominated solution for which all objective functions are unchanged or improved and there is at least one, which is strictly improved. For a set of feasible solutions *X*, the set of nondominated solutions, denoted as *S*, is defined as follows:

$$S = \{x : x \in X\},\ x' \in X \text{ such that } Z_q(x') > Z_q(x)$$
$$\text{for some } q \in \{1,2,.....,p\} \text{ and } Z_k(x') \geq Z_k \text{ for all } k \neq q\ \} \tag{4}$$

Each nondominated solution $x \in S$ implies values for each of the *p* objectives *Z(x)*. The collection of all the *Z(x)* for $x \in S$ yields the nondominated set *Z(S)*. The nondominated solution is defined in the objective space, and it is a subset of the feasible region in the objective space, i.e. $Z(S) \subseteq Z(X)$. From the definition of *S* it is obvious that if one objective function improves by moving from one nondominated solution to another, then one or more of the other objective functions must decrease in value.

Multi-objective programming problems can be continuous or discrete. Continuous formulation requires analytical description of the objective function vector. One example of the continuous formulation is a linear multi-objective problem where:

1. All the objective functions are linear, that is, for *i* = 1, …*i*

$$f_i(x) = c_{i1}x_1 + c_{i2}x_2 + ... + c_{in}x_n \tag{5}$$

where the c_{i1}, c_{i2} ….., c_{in} are given constants.

2. All constraints are described by linear inequalities of the form

$$a_{j1}x_1 + a_{j2}x_2 + ... + a_{jn}x_n \begin{matrix} \leq \\ = \\ \geq \end{matrix} b_j \tag{6}$$

where the a_{j1}, a_{j2} ….., and b_j are given constants

A problem is called discrete if the feasible set X contains only finite number of points. For example, if the decision maker can only choose from a finite number of alternatives, then X is necessarily finite and the problem is discrete. Consider a problem where m alternatives are to be evaluated by n decision makers, who are using p objectives. The general conceptual decision matrix for this discrete multi-objective multi-participant problem is shown in Table 1.

Table 1: Conceptual decision matrix for a discrete multi-objective multi-participant decision problem

	O_1	…	O_p
A_1	a_{11}	…	a_{1p}
…	…	…	…
A_m	a_{m1}	…	a_{mp}
DM_1	w_{11}	…	w_{p1}
…	…	…	…
DM_n	w_n	…	w_{pn}

In Table 1, A denotes the alternative, O is the objective and DM is the decision maker. The preference of the decision maker k (k = 1 …..n) for the objective j (j = 1….p) is expressed by w_{jk} and a_{ij} is the performance evaluation of the alternative i (i = 1…..m) for each objective j. The objectives as well as the performance evaluations can either be quantitative or qualitative.

The classical outcome of the decision matrix is the ranking of the alternatives. To obtain that, a number of steps are necessary like establishing the preference structure, the weights and also the performance evaluations. Among the multi-objective methods, some perform the ranking, some establish the preference structure, and some methods come up with the values inside the matrix. Some methods have the ability to incorporate qualitative data into the analysis while other methods are capable of including multiple decision makers in the decision making process.

Flood management is a typical example of multiobjective problem, where the objectives could be to minimize the damage to human lives and property; to minimize the depth of floodwater in flood inundated region; to effectively assess the damages as fast as possible; and to minimize the time to reach help to the flood victims. Many flood protection alternatives, such as, controlling the flood through floodway gate operations or building a dike around any region are spatially varying features. Some of the criteria values, such as, floodwater depth and damages are also spatially variable. There are numerous possibilities of uncertainties being involved in the matrix of alternatives and criteria values. These uncertainties may arise due to weights assigned to each of the criterion or in the criteria values itself. So the general flood management can be addressed by multiobjective analysis. However, spatial variability calls for a modified approach. Tkach and Simonovic (1997) introduced the Spatial Compromise Programming (SCP) to account for the spatial variability in multiobjective problems. Uncertainties can be addressed using probability theory but in this case due to the various kinds of uncertainties a new paradigm is necessary. Bender and Simonovic (2000) explained how uncertainties can be addressed using their Fuzzy Compromise

Programming (FCP) method. An obvious need to link the SCP and FCP can be noted here so as to address the spatial variability and account for uncertainties.

With above background a new approach, called herein as Spatial Fuzzy Compromise Programming (SFCP), is being proposed here in which Compromise Programming (CP), Spatial Compromise Programming (SCP), Fuzzy Compromise Programming (FCP) and Geographic Information System (GIS) are the main methodological building blocks. Basically, Spatial Fuzzy Multi Objective Analysis is a new MCDM technique, which can address spatial variability through the use of GIS environment and account for uncertainties through the use of fuzzy set theory. Our aim is to find the best flood protection alternative (based on multiple criteria) for each location (5 x 5 m grid) in the entire region of interest and present it in the GIS environment.

2.1 Problem Formulation

In this study a set of potential flood protection alternatives and a set of criteria/objectives have been considered. The main objective is to carry out MCDM to arrive at the best alternative for each location by accounting for uncertainties and spatial variability in the various elements of flood management process. The uncertainties are inherent in the representation of any natural process. They are also associated with input data; criteria values; equipment accuracy; and lack of knowledge. Spatial variability is one of the key features in any flood management/protection planning process due to the importance of special characteristics of the region on the physical and decision making processes of flood management. Spatial Compromise programming (SCP) (Tkach and Simonovic, 1997), which is an extension of CP, has been chosen as the basic technique to apply MCDM to this particular problem. As with CP, in the application of SCP, the distance from an ideal point expressed through so-called distance metric is the basis on which alternatives are evaluated. However, with the new approach, rather than selecting a single alternative for the whole region of interest, a distance metric is calculated for each location in the region. 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. Therefore, an individual rater cell within the feature image represents each location within the region of interest for which a distance metric is calculated.

Fuzzy compromise programming (FCP) as developed by (Bender and Simonovic, 2000) applied to a general form analogous to the original “crisp” version, allows a family of possible scenarios to be reviewed without the aid of sensitivity analysis – while maintaining indications of possibility and relevance. Group decision making can also be supported through collective opinions, including membership functions designed to reflect conflicting judgments. Integration of SCP with FCP can address the desired spatial variability with capability to address uncertainties in the flood management process. The usefulness of general fuzzy approach to Compromise Programming comes from the incorporation of subjective uncertainty. However, it is not necessary to fuzzify all the inputs to compute fuzzified distance metric. Uncertainties associated with the simulation of natural hydrologic processes that are being represented and the uncertainties arising from the data used along with the accuracy of equipments used to collect the data can well be addressed through probabilistic approaches. Lack of knowledge that brings in some vagueness, can be address with the help of fuzzy theory. Therefore, some of the inputs in the basic multi objective problem matrix (Table 1) can be fuzzy, some can be probabilistic, while others can remain deterministic.

Foundation of the proposed new methodology, however, is CP. As described by Zeleny (1973), CP is a MCDM technique, which can be used to identify the best compromise solution from a number of potential alternatives. The best alternative selected would be the one that is closest to the ‘ideal solution’ (Figure 1). The point that provides the extreme value for each of the criteria considered in the analysis would be the ‘ideal solution’.

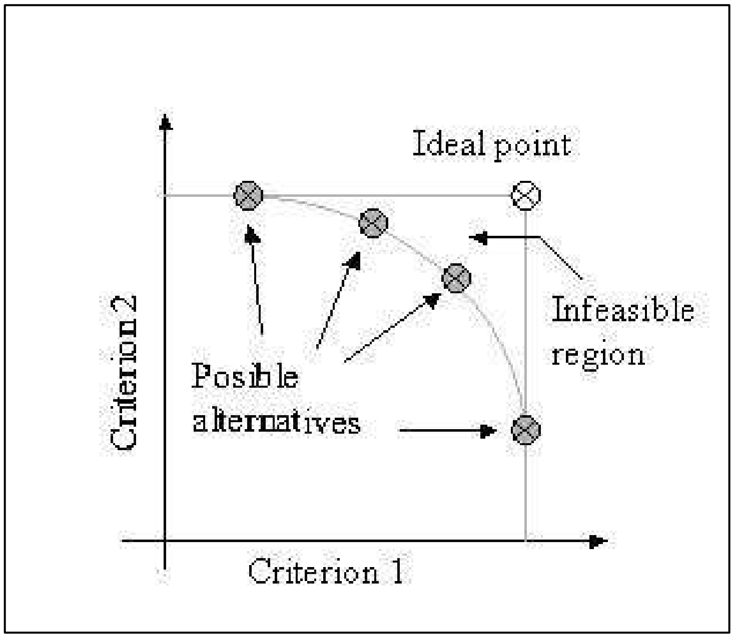

Figure 1: An illustration of Compromise Programming

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 distance metric is typically selected as the 'best compromise solution'. Equation (7) is the formula used to compute the distance metric values (L_j) for a set of n criteria and m alternatives.

$$L_j = \left[\sum_{i=1}^{n} w_i^p \left| \frac{f_i^* - f_{i,j}}{f_i^* - f_{i,w}} \right|^p \right]^{1/p} \tag{7}$$

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

In Equation (7), each criterion is to be given a level of importance, or weight, provided by the decision makers. The parameter *p* is used to represent the importance of the maximal deviation from the ideal point. If $p = 1$, all deviations are weighted equally; if $p = 2$, the deviations are weighted in proportion to their magnitude. Typically, as *p* increases, so does the weighting of the deviations. As Tecle et al. (1998) put it, "varying the parameter *p* from 1 to infinity, allows one to move from minimizing the sum of individual regrets (i.e., having a perfect compensation among the objectives) to minimizing the maximum regret (i.e., having no compensation among the objectives) in the decision making process. The choice of a particular value of this compensation parameter *p* depends on the type of problem and desired solution. In general, the greater the conflict between players, the smaller the possible compensation becomes."

Spatial Compromise Programming (SCP) (Tkach and Simonovic, 1997) was introduced to include the spatial variability in the criteria, which is often the case in water resources management. For example, in flood control, the impacts produced by flooding are not the same for all locations within the flood affected region. Implementation of a particular flood protection measure may reduce flood impacts at one location, while providing no protection at all for another. Using the principles of GIS, spatial considerations can be included into multi criteria decision making. The determination of the best spatial location for an alternative according to a predetermined set of criteria has been demonstrated in literature (Carver, 1991; Pereira and Duckstein, 1993). Unlike, CP, rather than determining a single value per alternative, a distance metric is calculated for each impacted location, for each alternative. In this approach the region is represented by a raster feature image of the area of interest. Thus an individual raster cell within the feature image represents each location within the region of interest, for which a distance metric is calculated. Criteria values associated with each of the alternatives are contained within sets of criteria images, which are georeferenced with the feature images of buildings, roads and agricultural fields. Figure 2 illustrates this process graphically.

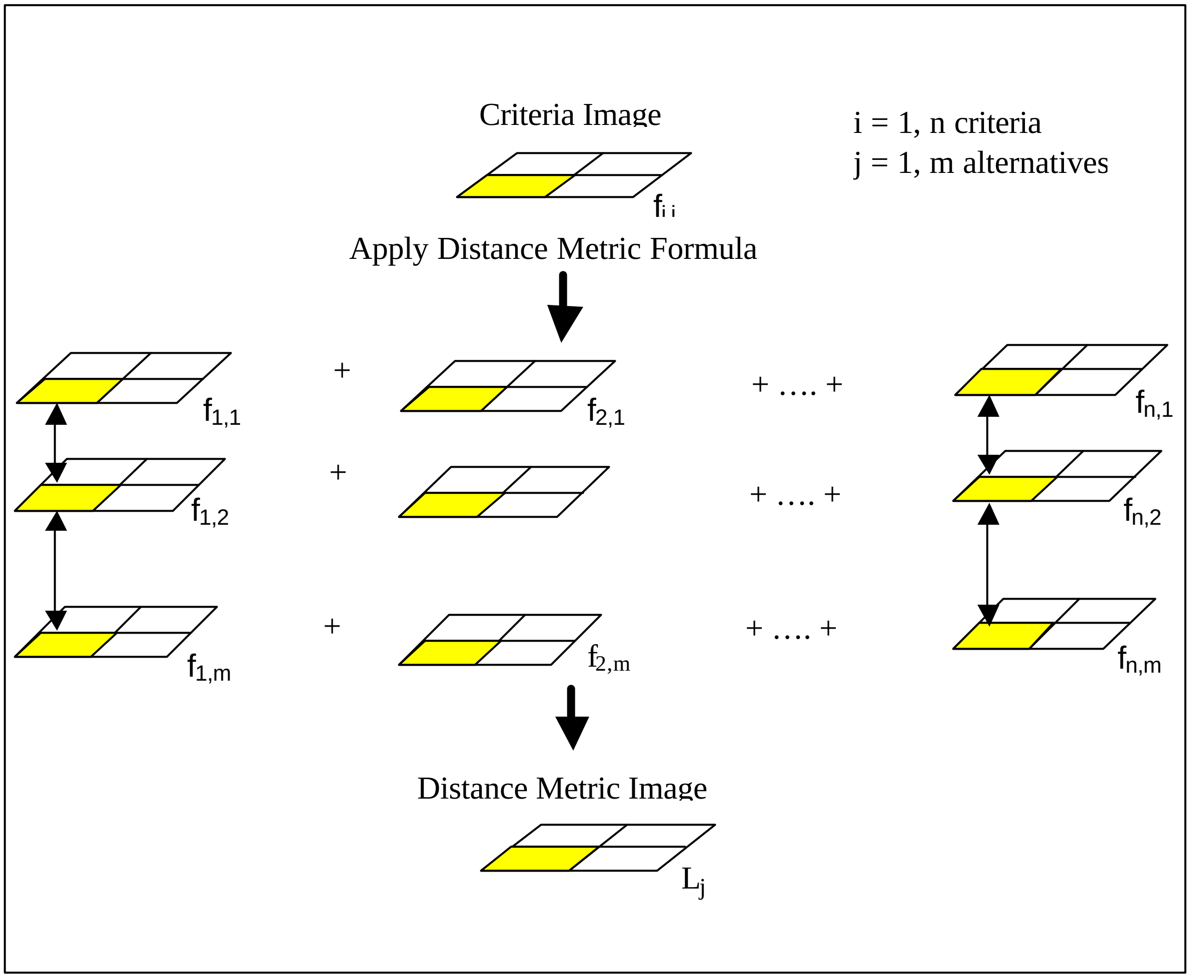

Figure 2: Cell by cell calculation of distance metric values

Equation (7) will take the form of Equation (8) when the computations are carried out on a cell by cell basis.

$$L_{j,x,y} = \left[\sum_{i=1}^{n} w_i^p \left| \frac{f_{i,x,y}^* - f_{i,j,x,y}}{f_{i,x,y}^* - f_{i,w,x,y}} \right|^p \right]^{1/p} \quad (8)$$

where: L_j is the distance metric; f_i^* is the optimal value of the i[th] criteria; $f_{i,j}$ is the value of the i[th] criteria for alternative j; $f_{i,w}$ is the worst value of i[th] criteria; 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; x = 1, a rows in the image; y = 1, b columns in the image; a is the number of rows in the image; and b is the number of columns in the image

In Fuzzy Compromise Programming (FCP) approach (Bender and Simonovic, 2000), the transformation of a distance metric to a fuzzy set can be accomplished by changing all inputs from crisp to fuzzy and applying the fuzzy extension principle. However, it should be noted that some of the inputs could remain in deterministic form provided the level of confidence about their accuracy is satisfactorily high. In this way a combination of fuzzy and deterministic inputs can also be handled by FCP approach. Measurement of distance between an ideal solution and the perceived performance of an alternative can no longer be given as a single value, because many distances are at least somewhat valid. Choosing the shortest distance to the ideal solution is no longer a straight forward ordering of distance metrics, because of overlaps and varying degrees of possibilities. The resulting fuzzy distance metric (Equation 9) contains a great amount of additional information about the consequences of a decision and the effect of subjectivity. Non-fuzzy distance-based techniques measure the distance from an ideal point, where the ideal alternative would result in a distance metric, $L : X \rightarrow \{0\}$. In the Fuzzy Compromise Programming approach, the distance is fuzzy, such that it represents all of the possible valid evaluations, indicated by the degree of possibility or membership value. Alternatives, which tend to be closest to the ideal solution, may be selected.

$$\tilde{L}_j = \left[\sum_{i=1}^{n} \tilde{w}_i^{\tilde{p}} \left| \frac{\tilde{f}_i^* - \tilde{f}_{i,j}}{\tilde{f}_i^* - \tilde{f}_{i,w}} \right|^{\tilde{p}} \right]^{1/\tilde{p}} \qquad (9)$$

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

Literature is available on the techniques for encoding information in a fuzzy set in order to generate input fuzzy sets. Articles on demonstrating decision problems with qualitative or subjective criteria are many. Fuzzy sets are able to capture many qualities of relative differences in perceived value of criteria among alternatives. Placement of modal values, along with curvature and skew of membership functions can allow decision makers to retain what they consider degree of possibility for subjective criteria values. As a subjective value, criteria weights may be more accurately represented by fuzzy sets (Despic and Simonovic, 2000). Another subjective element is generation of these fuzzy sets. It may be difficult to get honest opinions about degree of fuzziness from a decision maker. It might actually be more straightforward to generate fuzzy sets for weights when multiple decision makers are involved. Then, at least, voting methods and other techniques are available for producing a composite, collective, opinion, regardless, more information can be provided about valid weights from fuzzy sets than from crisp weights.

In Equation (8), p, is likely the most uncertain element of distance metric computation. There is no single acceptable value of p for every problem and also, it is not related to problem information in any way except by providing parametric control over interpretation of distance. Fuzzification of the distance metric exponent, p, can take many forms but in a practical way it might be defined by a triangular fuzzy set with a mode of 2. Similarly, weights w_i can be fuzzified to account for indecisiveness of their boundary values, for example, a value of 0.5 could be defined as approximately 0.5. This means that fuzzy boundaries of weight values will take care of the uncertainties associated with crispness. Expressing possibility values with fuzzy inputs allows experience to play a significant role in the expression of input information. The shape of a fuzzy membership function expresses the experience or the interpretation of a decision maker.

In the SCP 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, for convenience Equation (9) has been rewritten in such a way that the better the alternative, the larger the distance metric value (Tkach and Simonovic, 1997). Thus Equation (9) can acquire a modified form as shown in Equation (10). This equation will produce the same ranking of alternatives as the fuzzified distance metric formula shown in Equation (9).

$$\tilde{L}_j = \left[\sum_{i=1}^{n} \tilde{w}_i^{\tilde{p}} \left| \frac{\tilde{f}_{i,w} - \tilde{f}_{i,j}}{\tilde{f}_i^{*} - \tilde{f}_{i,w}} \right|^{\tilde{p}} \right]^{1/\tilde{p}} \qquad (10)$$

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

Spatial Fuzzy Compromise Programming (SFCP) works on the same principle as that of CP and SCP. The additional information that goes as input for the computation of distance metric is in the form of fuzzified criteria images, fuzzified parameter p and fuzzified weights w. This fuzzification has been proposed to account for the vagueness or uncertainty in the entire process of decision making. The process of cell by cell fuzzification of each input image can be carried out using appropriate membership function, such as, gaussian, triangular-shaped, sigmoidally-shaped or Z-shaped.

Modification of Equation (10) with inclusion of fuzzy inputs and spatial consideration will give the distance metric formula for SFCP as shown in Equation (11).

$$\tilde{L}_{j,x,y} = \left[\sum_{i=1}^{n} \tilde{w}_i^{\tilde{p}} \left| \frac{\tilde{f}_{i,w,x,y} - \tilde{f}_{i,j,x,y}}{\tilde{f}^{*}_{i,x,y} - \tilde{f}_{i,w,x,y}} \right|^{\tilde{p}} \right]^{1/\tilde{p}} \tag{11}$$

where: $\tilde{L}_{j,x,y}$ is the fuzzy distance metric; $\tilde{f}_{i,w,x,y}$ is the fuzzy worst value of i^{th} criteria; $\tilde{f}_{i,j,x,y}$ is the fuzzy value of the i^{th} criteria for alternative *j*; $\tilde{f}^{*}_{i,x,y}$ is the fuzzy optimal value of the i^{th} criteria; $\tilde{p}$ is a fuzzified parameter ($1 \le p \le \infty$); $\tilde{w}_i$ are fuzzified weights indicating decision maker preferences; $i = 1$, n criteria; $j = 1$, m alternatives; $x = 1$, *a* rows in the image; $y = 1$, *b* columns in the image; *a* is the number of rows in the image; and *b* is the number of columns in the image.

Using the values in the fuzzified distance metric images the best alternative is determined for each location. The fuzzified 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 fuzzified distance metric value for each raster cell is selected as the best. This cell be cell comparison between the alternatives is undertaken for each location in the region of interest. This process is illustrated in mathematical form by Equation (12). Based on this comparison, an image identifying the best alternative for each location is produced. Each cell within this image is shown with corresponding 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.

$$\max\left\{\tilde{L}_{j,x,y} = \left[\sum_{i=1}^{n} \tilde{w}_i^{\tilde{p}} \left|\frac{\tilde{f}_{i,w,x,y} - \tilde{f}_{i,j,x,y}}{\tilde{f}_{i,x,y}^{*} - \tilde{f}_{i,w,x,y}}\right|^{1/\tilde{p}}\right]^{\tilde{p}}\right\} \tag{12}$$

where: $\tilde{L}_{i,x,y}$ is the fuzzy distance metric; $\tilde{f}_{i,w,x,y}$ is the fuzzy worst value of the i^{th} criteria; $\tilde{f}_{i,j,x,y}$ is the fuzzy value of the i^{th} criteria for alternative j; $\tilde{f}_{i,x,y}^{*}$ is the fuzzy optimal value of the i^{th} criteria; $\tilde{w}_i$ are fuzzified weights indicating decision maker preferences; $\tilde{p}$ is a fuzzified parameter ($1 \leq \tilde{p} \leq \infty$); $i = 1, n$ criteria; $j = 1, m$ alternatives; $x = 1, a$ rows in the image; $y = 1, b$ columns in the image; a is the number of rows in the image; and b is the number of columns in the image

2.2 Solution Methodology

In this section, a step-by-step evaluation of the solution process has been described. In this study flood protection alternatives have been evaluated and ranked using the proposed new techniques of SFCP. Initial data requirements include:

- Digital Elevation Model (DEM) of the region of interest;
- Separate feature images of buildings, roads, agricultural fields and any other features, which might suffer damages in the region of interest;
- Hydraulic data, including river reach cross section profile, expansion and contraction coefficients, Manning's n; and
- Flood event data set, which will be the basis of flood protection alternatives' simulation process.

Next step is to consider a set of potential flood protection alternatives that are feasible in the region of interest. Further, a set of relevant criteria/objectives needs to be decided upon. For example, in case of flood protection planning one of the criteria could be to minimize the depth of floodwater. Minimum damage to property and people is another potential criterion.

Having decided upon the criteria, a raster image is prepared for each of the criteria in which each raster cell contains the criteria values for all distinct geographic locations. This is accomplished using a combination of the flooded feature images, the water surface elevations as contained in the image, and the DEM of the region of interest. Raster cells in locations which were unaffected by floodwaters retain a value of zero. In this way an image containing the criteria values for all flooded locations in the study region can be produced for each alternative.

According to SCP technique, separate images showing the best and the worst criteria values for each location in the study region, are also necessary. Dollar value of damages to property and people can be estimated using appropriate relationships. Section 3 describes the procedure for the Red River Bain case study.

Criteria values associated with each of the alternatives are contained within sets of criteria images, which are georeferenced with the feature images. 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 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. Using GIS the spatial distribution of the criteria values are captured.

The best and the worst criteria values are 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. This way each criterion 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 or absolute 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 best and the 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.

Based on the criteria images, and the decision maker's preferences, a distance metric 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. As illustrated in Figure 3, the fuzzified distance metric values within the images are calculated by comparing impacts for each location on a cell by cell basis between all alternatives and applying the decision makers' preferences, which are in fuzzy form as well. 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. Fuzzified distance metrics are then defuzzified for ranking purpose. Spatially variable ranking of flood protection alternatives is carried out to come up with the final picture of preference of each alternative for each location in the region of interest.

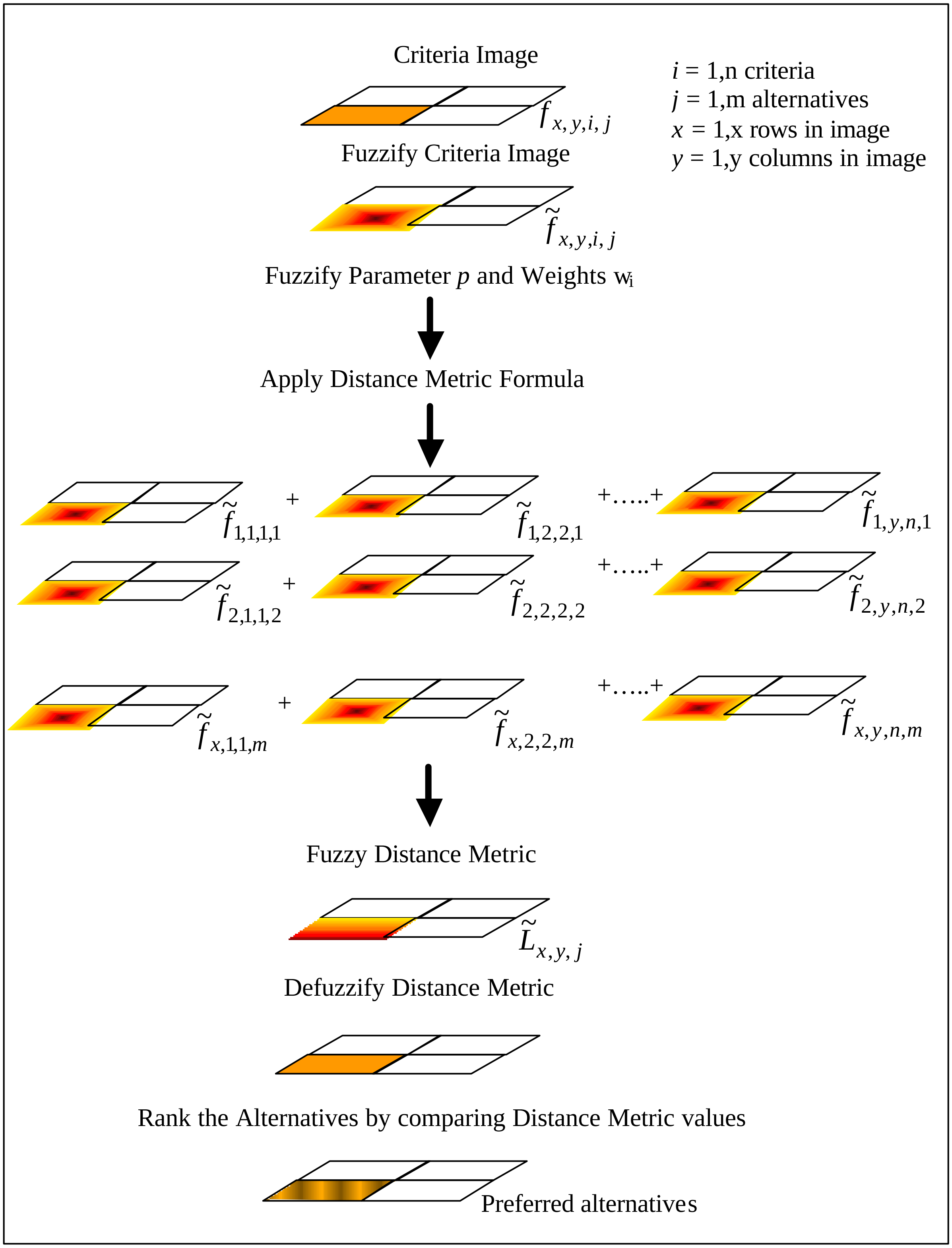

Figure 3: SFCP procedure for ranking of flood protection alternatives.

3. IMPLEMENTATION OF SFCP TO FLOOD DECISION MAKING – RED RIVER CASE STUDY

A floodplain analysis of the Red River Valley, has been selected to demonstrate the capabilities of the proposed Spatial Fuzzy Compromise Programming (SFCP) technique for Multi Objective Decision Analysis. This area is located in the south-central portion 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 River and Assiniboine River. Other communities of significant size further upstream in the Red River Valley include the towns of St. Adolphe, St. Agathe, Morris, and Emerson.

The Red River Valley, which borders North Dakota and Minnesota in the US and flows north toward Lake Winnipeg in Manitoba, Canada, is very prone to flooding and has historically (1826, 1950, 1979, 1997) incurred extensive damages to both urban and agricultural areas from floodwaters. 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 2,331 square kilometer 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 9.2 m above datum within the City of Winnipeg (Bumsted, 1993). In this flood roughly 1,658 square kilometer 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. The 1997 flood was called the “flood of the century” due its severe nature (Figure 4).

Figure 4: Red River flooding in 1997

(Source: *http://www.geo.mtu.edu/department/classes/ge404/mlbroder/*)

The Red River reached its peak in Winnipeg early May 4, 1997 causing the worst flooding the region has seen since 1852. The peak discharge near the City of Winnipeg reached 73,152 m^3/sec. Flows in downtown Winnipeg were affected by the Red River

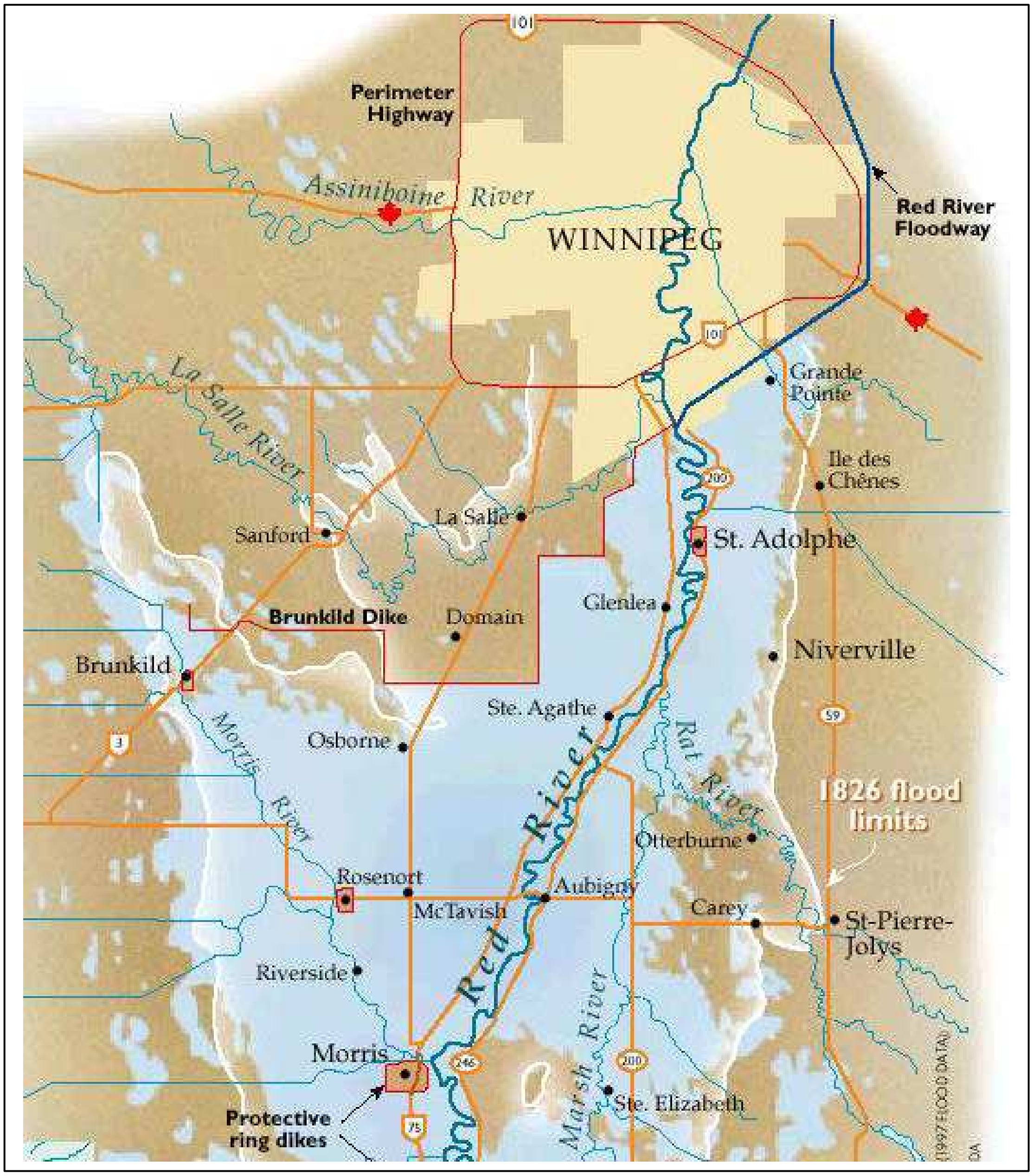

Figure 5: 1997 flooding in Red River (Source: Manitoba Centre for Remote Sensing website)

Floodway and Assiniboine River flood control works. Some 2,000 square kilometer of Red River Valley were under water. The flood crest from the Red River emptied into

Lake Winnipeg May 8, 1997 ending the worst flooding in the Red River Valley ever on record. Figure 5 shows the entire area covered with 1997 flood in blue.

For this particular study, community of St. Adolphe has been taken into consideration. A schematic diagram of the entire Red River Valley near and around the City of Winnipeg is shown in Figure 6.

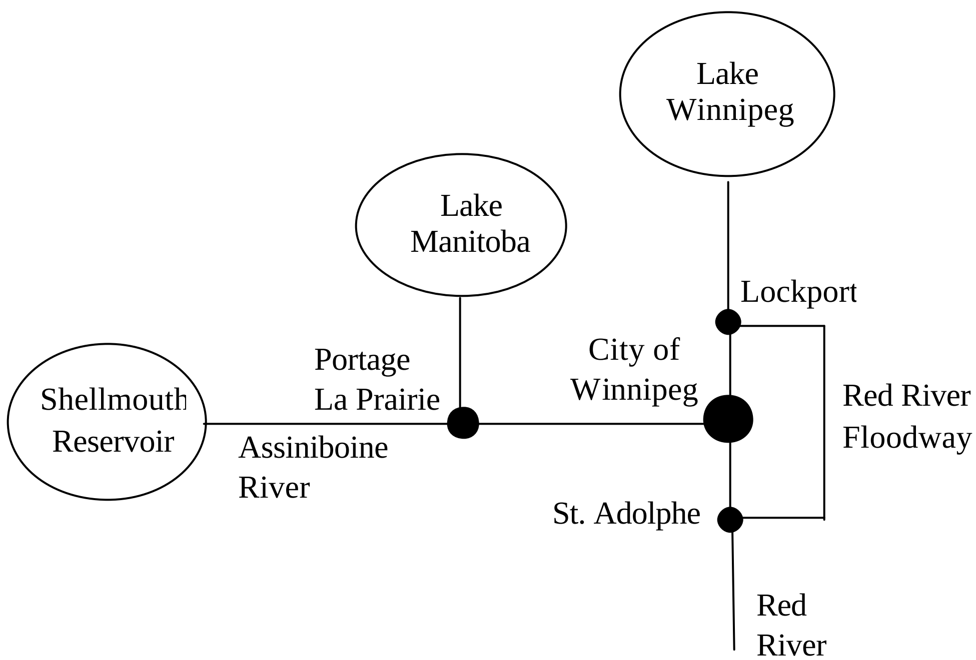

Figure 6: Flood control systems for the City of Winnipeg and surrounding area (Source: Tkach and Simonovic, 1997).

3.1 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 6) include (i) dikes along both the Red and Assiniboine Rivers; (ii) flood pumping stations within the City of Winnipeg; (iii) Shellmouth Reservoir; (iv) Portage diversion; and (v) Red River Floodway. For the purpose of developing the methodology for proposed Spatial Fuzzy Compromise Programming (SFCP), flood protection measures for the community of St. Adolphe has been considered. Thus two of the five flood protection measures are thought to be appropriate for this study.

3.1.1 Dikes

The dikes were constructed strategically in order to provide protection to those areas with a high risk of incurring heavy damages. Along the Red River (outside of the City of Winnipeg), all larger communities (Emerson, Letellier, Dominion City, St. Jean Baptiste, Morris, Rosenort, Brunkild, and St. Adolphe) are surrounded by ring dikes composed of both earthen material and sheet pilling. All the dikes are being constructed such that they would be broad enough to permit the addition of smaller temporary dikes in the even of a larger flood. The protection level provided by the dikes is equal to the water elevation, which occurred during the 1950 flood (Rannie, 1980).

3.1.2 Red River Floodway

The Red River Floodway, Manitoba's largest flood protection project, was completed in 1968. The floodway is a 48.28 km long channel, with a flow capacity of 54,864 m^3/sec, 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 (Figure 6). The flow of water within the Red River is unaffected by the floodway until the discharge reaches 27,432 m^3/sec. 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 dikes, which extend 43.45 km 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).

3.2 Flood Protection Alternatives

Three flood protection alternatives that are considered in this study are as follows:

1. Build a dike around the community in the region of interest that needs to be protected. This dike has been simulated only at the right bank of the river to protect the community of St. Adolphe;

2. Alteration of controlled floodway operation so as to let more floodwater flow through the floodway in order to protect the larger city downstream. This is achieved by raising the floodway gate height in such a way that the water surface elevation at the floodway entrance is increased by 1 meter above the normal level. This alternative will be referred to herein as Floodway 1; and

3. Alteration of controlled floodway operation so as to let less floodwater flow through the floodway in order to protect a community upstream. This is achieved by lowering the floodway gate height in such a way that the water surface elevation at the floodway entrance is decreased by 1 meter below the normal level. This alternative will be referred to herein as Floodway 2.

3.3 Data Requirement

3.3.1 GIS data

The floodplain analysis of the Red River Valley is selected as a case study in order to demonstrate the benefits of the new SFCP technique for addressing the conflict between upstream and downstream communities. The study focus is a 2.015 x 1.720 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. In normal operational process 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. Figure 7 shows the DEM of the study region, which is part of the basic data set for implementation of the proposed SFCP. This 5-meter resolution DEM was acquired from LIDAR (LIght Detection And Ranging) remote sensing data. Appendix E gives more details on the actual data files used for this case study.

Feature image data sets were acquired for the purpose of damage assessment due to flooding. In Figure 8, buildings in St. Adolphe are visible in yellow, roads can be seen as the straight lines around the buildings and also across the river and the agricultural fields are illustrated (polynomials) in shades of yellow. Red River is shown in purple. Please note that the legend on the right side denotes the elevation of the features in the region.

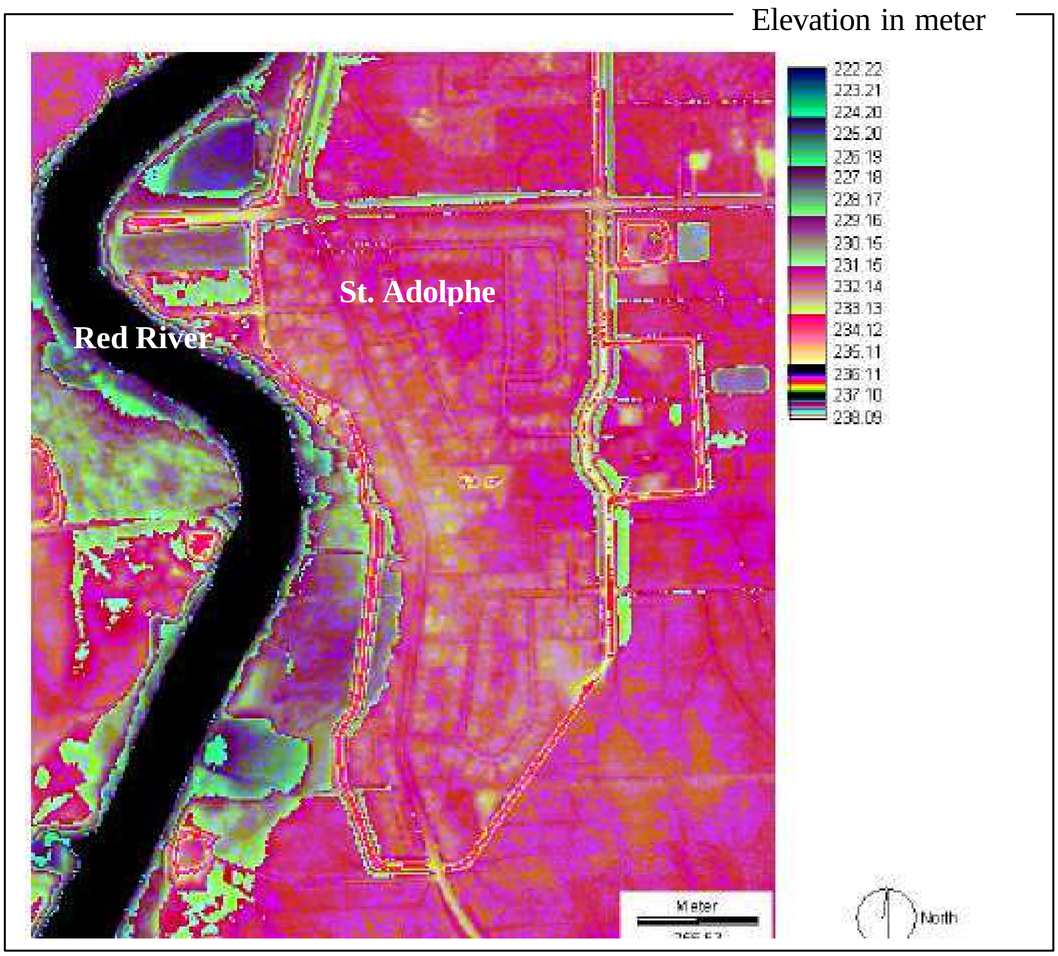

Figure 7: DEM of study region of St. Adolphe along the Red River.

Figure 8: Feature image comprising of buildings (clusters in yellow), roads (lines) and agricultural fields (yellow polynomials) in St. Adolphe region

3.3.2 Hydraulic Data

The next step is to acquire hydraulic data of the Red River in the region of interest, which is needed for HEC-RAS hydraulic simulations. Using HEC-RAS hydraulic model the simulation of all three alternatives is performed. The U.S. Army Corps of Engineer's River Analysis System (HEC-RAS) is a software capable of one-dimensional water surface profile calculations for steady gradually varied flow in natural or constructed channels (Hydrologic Engineering Center, 2001). It is an integrated system of software, designed for interactive use in a multi-tasking, multi-user network environment. The basic computational procedure is based on the solution of the one-dimensional energy equation. Energy losses are evaluated by friction (Manning's equation) and contraction/expansion (coefficient multiplied by the change in velocity head). The momentum equation is utilized in situations where the water surface profile is rapidly varied.

Water surface profiles are computed from one cross section to the next by solving the Energy equation with an interactive procedure called the standard step method. The Energy equation (13) is written as follows;

$$Y_2 + Z_2 + \frac{\alpha_2 V_2^2}{2g} = Y_1 + Z_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \qquad (13)$$

where: Y_1, Y_2 = depth of water at cross section; Z_1, Z_2 = elevation of the main channel inverts; V_1, V_2 = average velocities (total discharge/total flow area); α_1, α_2 = velocity weighting coefficients; h_e = energy head loss; and g = gravitational acceleration

A diagram showing the terms of the energy equation is shown in Figure 9.

The energy head loss (h) between two cross sections is comprised of friction losses and contraction or expansion losses. The equation for the energy head loss is as follows:

$$h_e = L\overline{S}_f + C\left|\frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g}\right| \qquad (14)$$

where: L = discharge weighted reach length; $\overline{S}_f$ = representative friction slope between two sections; and C = expansion or contraction loss coefficient

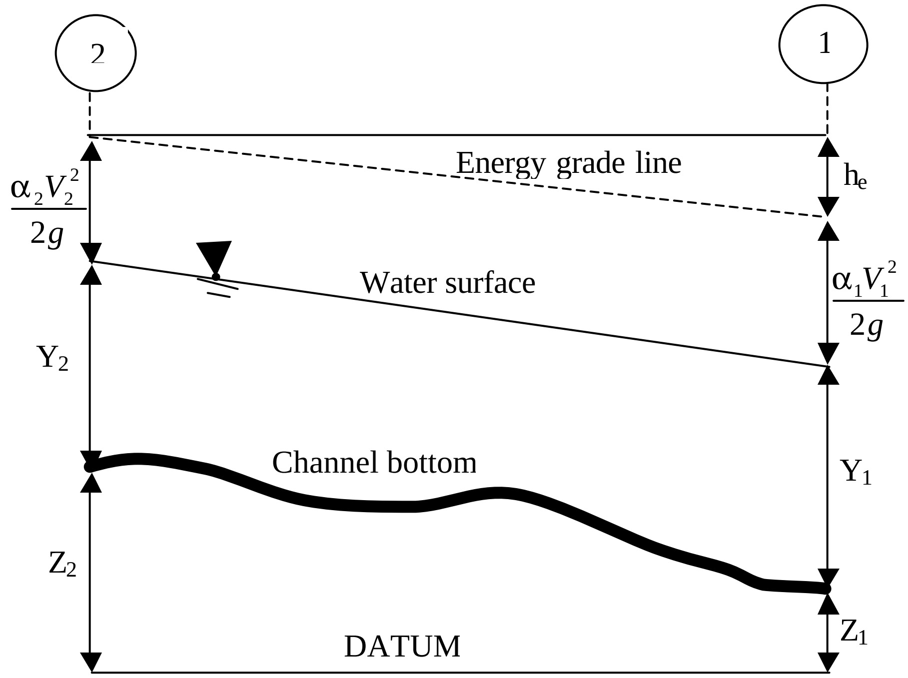

Figure 9: Representation of terms in the Energy equation (Source: Hydrologic Engineering Center, 2001)

The distance weighted reach length, L, is calculated as:

$$L = \frac{L_{lob}\overline{Q}_{lob} + L_{ch}\overline{Q}_{ch} + L_{rob}\overline{Q}_{rob}}{\overline{Q}_{lob} + \overline{Q}_{ch} + \overline{Q}_{rob}} \tag{15}$$

where: L_{lob}, L_{ch}, L_{rob} = cross section reach lengths specified for flow in the left overbank, main channel, and right overbank, respectively; and

$\overline{Q}_{lob}, \overline{Q}_{ch}, \overline{Q}_{rob}$ = arithmetic average of the flows between sections for the left overbank, main channel, and right overbank, respectively.

The determination of total conveyance and the velocity coefficient for a cross section requires that flow be subdivided into units for which the velocity is uniformly distributed. The approach used in HEC-RAS is to subdivide flow in the overbank areas using the input cross section n-value break points (locations where n-values change) as the basis for subdivision (Figure 10). Conveyance is calculated within each subdivision from the following form of Manning's equation:

$$Q = KS_f^{1/2} \tag{16}$$

$$K = \frac{1.486}{n} AR^{2/3} \tag{17}$$

where: K = conveyance for subdivision; n = Manning's roughness coefficient for subdivision; A = flow area for subdivision; and R = hydraulic radius for subdivision (area/wetted perimeter).

The program sums up all the incremental conveyances in the overbanks to obtain a conveyance for the left overbank and the right overbank. The main channel conveyance is normally computed as a single conveyance element. The total conveyance for the cross section is obtained by summing the three subdivision conveyances (left, channel, and right).

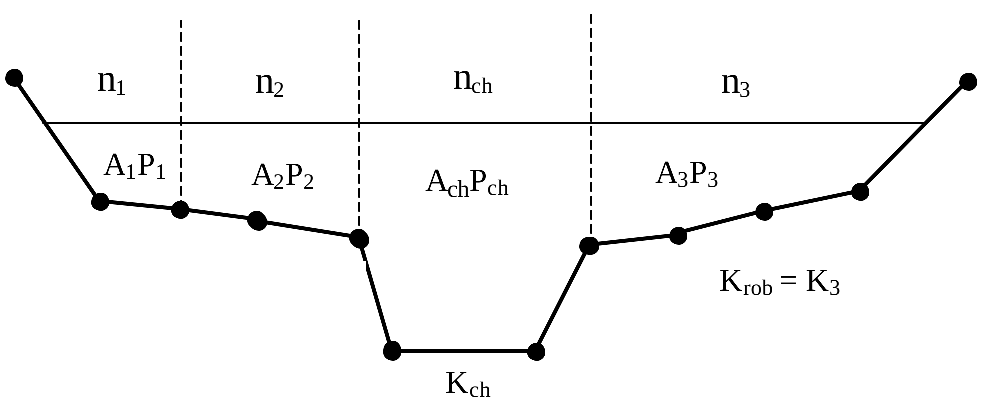

Figure 10: HEC-RAS default conveyance subdivision method (Source: Hydrologic Engineering Center, 2001)

Simulation of flood flows with simulated flood protection alternatives is carried out using HEC-RAS dike/levees options. In HEC-RAS user can also define different floodway gate types.

HEC-RAS data files for St. Adolphe region (river cross section profile; river flows and coefficients, such as, Manning's n; contraction and expansion coefficients), which had been calibrated for 1997 Red River flood event, were obtained from Manitoba Department of Natural Resources. The modified water surface elevation in the study region has been calculated using HEC-RAS program and the three flood protection alternatives. Details of HEC-RAS simulation for the case study are given in Appendix B. The results of these simulations are listed in Table 2.

Table 2: HEC-RAS simulations for three different alternatives.

Alternative	Total discharge at floodway entry point (m^3/sec)	Water surface elevation (m)
Dike	3650	232.89
Floodway 1	4730	233.83
Floodway 2	2900	231.71

3.4 Criteria to Evaluate Flood Protection Alternatives

Two criteria that exhibit a spatial variability are selected for evaluating the alternatives: (a) water depth; and (b) flood damage. The computational procedures necessary to produce the raster criteria images involve the use of a GIS software and data on damage curves for buildings, agriculture and roads.

The first criterion used in the evaluation of the alternatives is the floodwater depth for the study region. An image is prepared in which each raster cell contained the water depth for all distinct geographic locations. This has been accomplished using a combination of the flooded feature images, the water surface elevations as contained in the image, and the DEM of the region of interest. For all flooded areas, as indicated by the flooded feature image, the ground surface elevations in the DEM are subtracted from the simulated water surface elevation. Raster cells in locations which were unaffected by floodwaters retained a value of zero. In this way an image containing the water depths for all flooded locations in the study region is produced for each alternative.

According to SCP technique, separate images showing the best and the worst criteria values for each location the study region, are also required. For the floodwater depth criteria, the absolute minimum water depth has been considered the best criteria value. Actual maximum floodwater depths are used to represent the worst criteria values. The second criterion used in the evaluation of the alternatives is the dollar value of damage to flooded structure within the region of interest. For the very reason of simplicity in demonstrating the new proposed technique of SFCP, only three categories of damages have been considered in this study. KGS Group (2000) recommendations, which are based on 1997 flood event, are implemented to arrive at the dollar value damages associated with each of the three categories, namely, damage to buildings, damage to roads and damage to agricultural fields. KGS Group (2000) data are used to arrive at the depth-damage relationship to evaluate building damages as given in Equation (18)

$$y = 76879x^3 - 344873x^2 + 470283x + 538659 \tag{18}$$

where: y is dollar value of damage to buildings; and x is floodwater depth.

Damage to roads has been considered (KGS Group, 2000) as a relationship between dollar value of damage and total length of submerged roads as given in Equation (19).

$$rd = 18.889L^2 + 261.25L + 300000 \tag{19}$$

where: *rd* is dollar value of damage to roads; and *L* is total length of flooded roads.

Agricultural damage assessment depends on time of the year and the type of crop in the region of interest. Though, spatial variability in crop type would be there in the study region, accurate account of such raster data image could not be found. Therefore, only one crop, namely, R.S. Wheat, is assumed to be in the agricultural fields at the time of flooding. Using a relationship described in Equation (20), which is recommended by KGS Group (2000), dollar value of agricultural damage is assessed.

$$ad = \sum\left[(1 - yield) * (cp) * A * price\right] \tag{20}$$

where: ad is dollar value of agricultural damage; yield is expected yield (fraction of optimum) as a function of seed date; CP is crop percentage of a typical distribution (cp =1 in this case); A is area of cropland (arces); and price is three year average price of crop ($/bushel)

3.5 Solution of the Deterministic Problem Formulation

Deterministic approach to the problem of MCDM using SCP is the first step towards development of fuzzy approach. The deterministic solution is necessary first so that a comparison between the deterministic and fuzzy formulations could be made.

Using SCP, each of the three flood protection alternatives is evaluated for each location in the region of interest. Weights indicating the relative decision maker preferences towards the criteria and the importance of their maximum deviation from the ideal solution (accounted for by variable p in Equation (8)) are necessary input for SCP. In this case study, a single value of $p=2$ is used in the evaluation of all alternatives. Selection of this value is based on the results produced by Simonovic (1989), wherein, it is determined that a selection of $p=2$ can be used as a reasonable approximation of the best compromise alternative from a set of potential solution.

Another set of weights describes the decision maker's preference towards the two criteria. These weights are symbolized as w_i in Equation (8). 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 are being selected and are shown in Table 3.

Table 3: Weights w_i indicating decision-maker preferences

Criteria	Decision-Maker's Preferences (w_i)		
	Weight Set # 1	Weight Set # 2	Weight Set # 3
Flood water depth	0.5	0.1	0.9
Damages	0.5	0.9	0.1

The first weight set is selected to give equal level of importance to both of the criteria. The other two weight sets were chosen to represent the difference (to the order of extreme nature) in opinion and interests between various decision makers. A step by step procedure along with the actual file names used in this work is given in Appendix C.

Based on the criteria images, and the decision maker's preferences, a distance metric is produced for each alternative. Distance metric values for alternatives 'Dike', Floodway 1' and 'Floodway 2' for weight set # 1 are shown in Figures 11 to 13 respectively and Figure 14 shows the ranking of the three alternatives. The three alternatives' distance metric images for weight set # 2 are given in Figures 15 to 17, and Figure 18 illustrates the ranking for the three alternatives for weight set # 2. Figures 19 to 21 are distance metrics for 'Dike', 'Floodway 1' and 'Floodway 2' for weight set # 3. Ranking of alternatives for weight set # 3 is given in Figure 22.

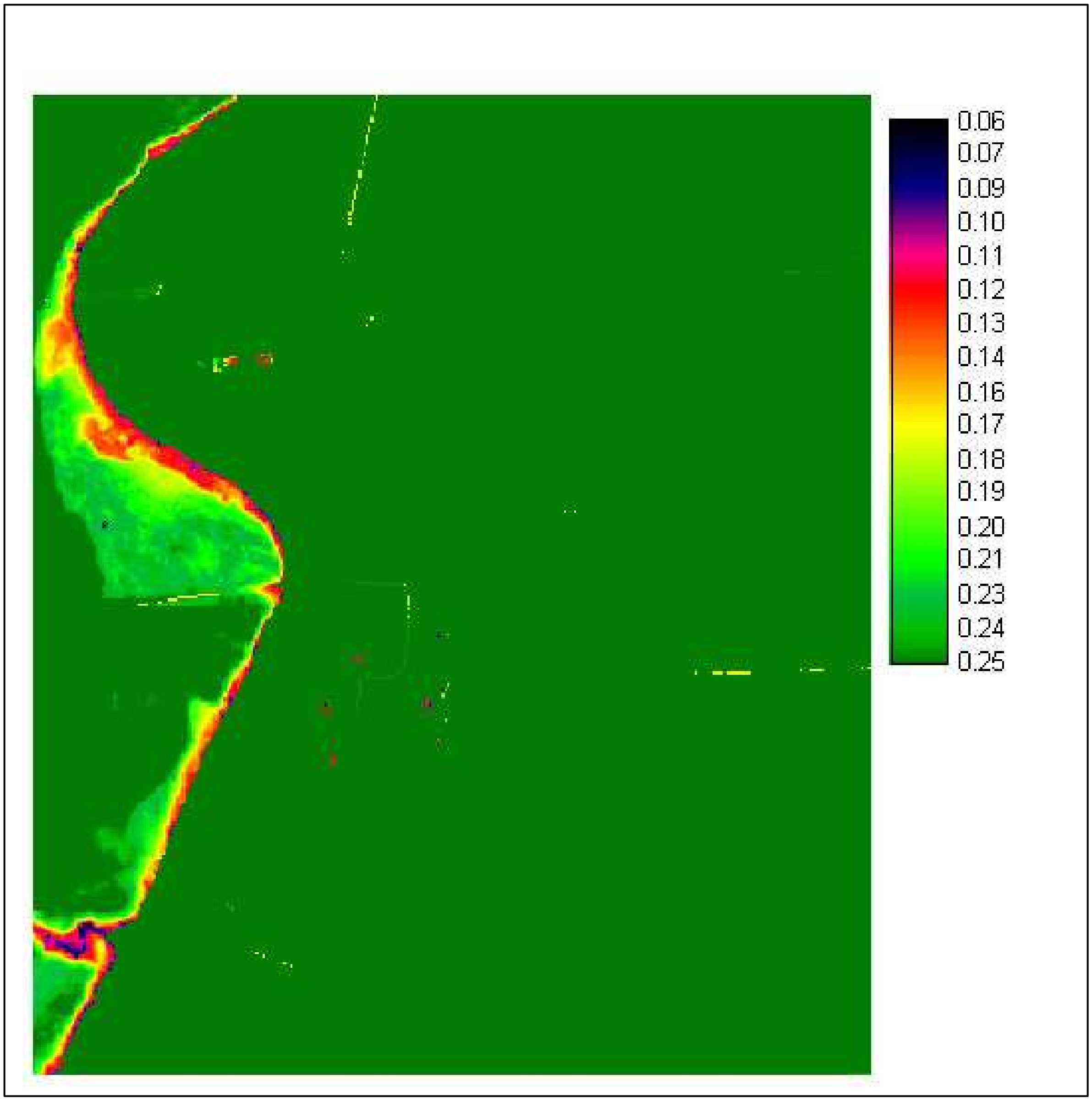

Figure 11: Distance metric image for alternative ‘Dike’ using SCP approach for weight set # 1

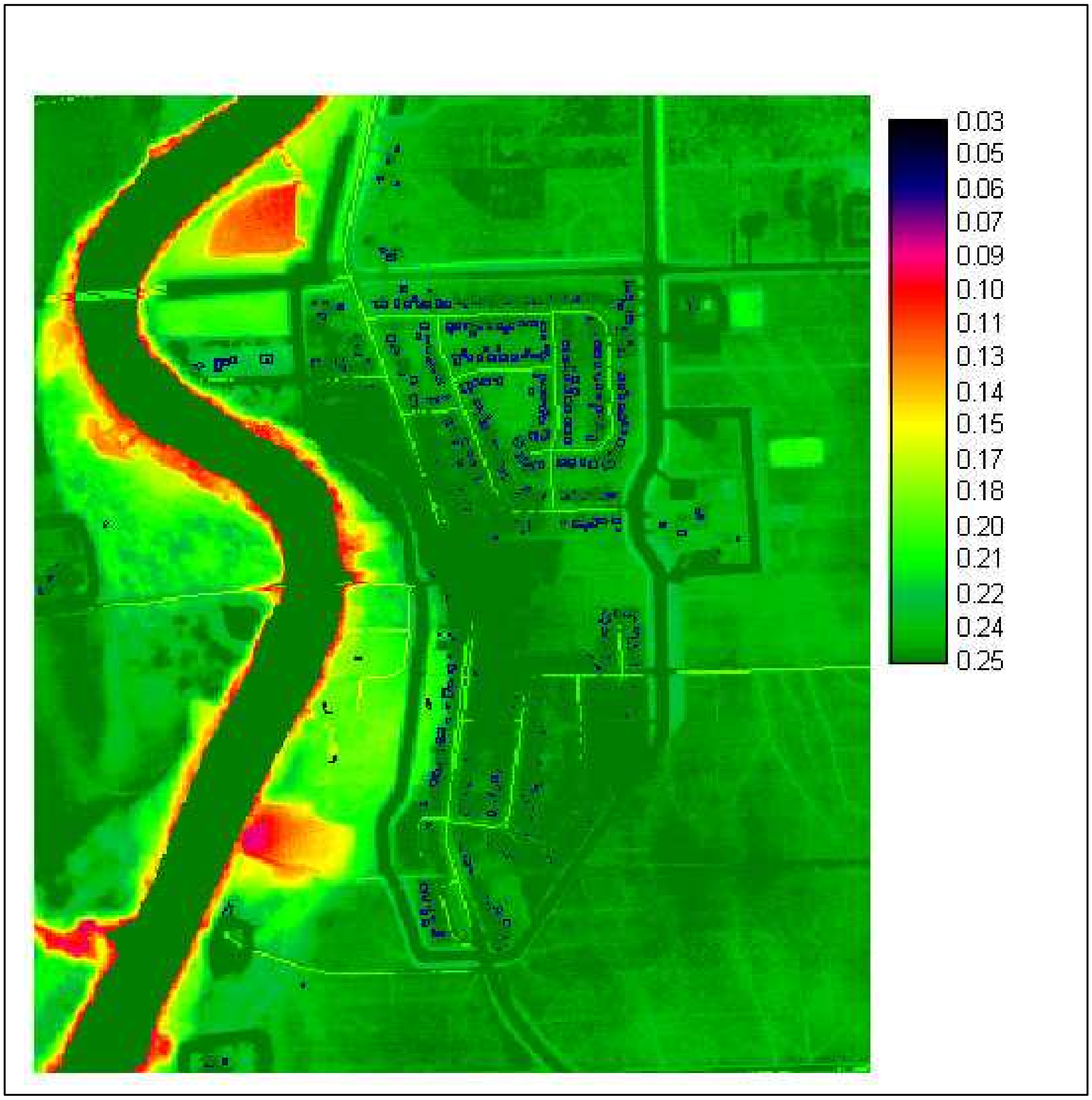

Figure 12: Distance metric image for alternative ‘Floodway 1’ using SCP approach for weight set # 1

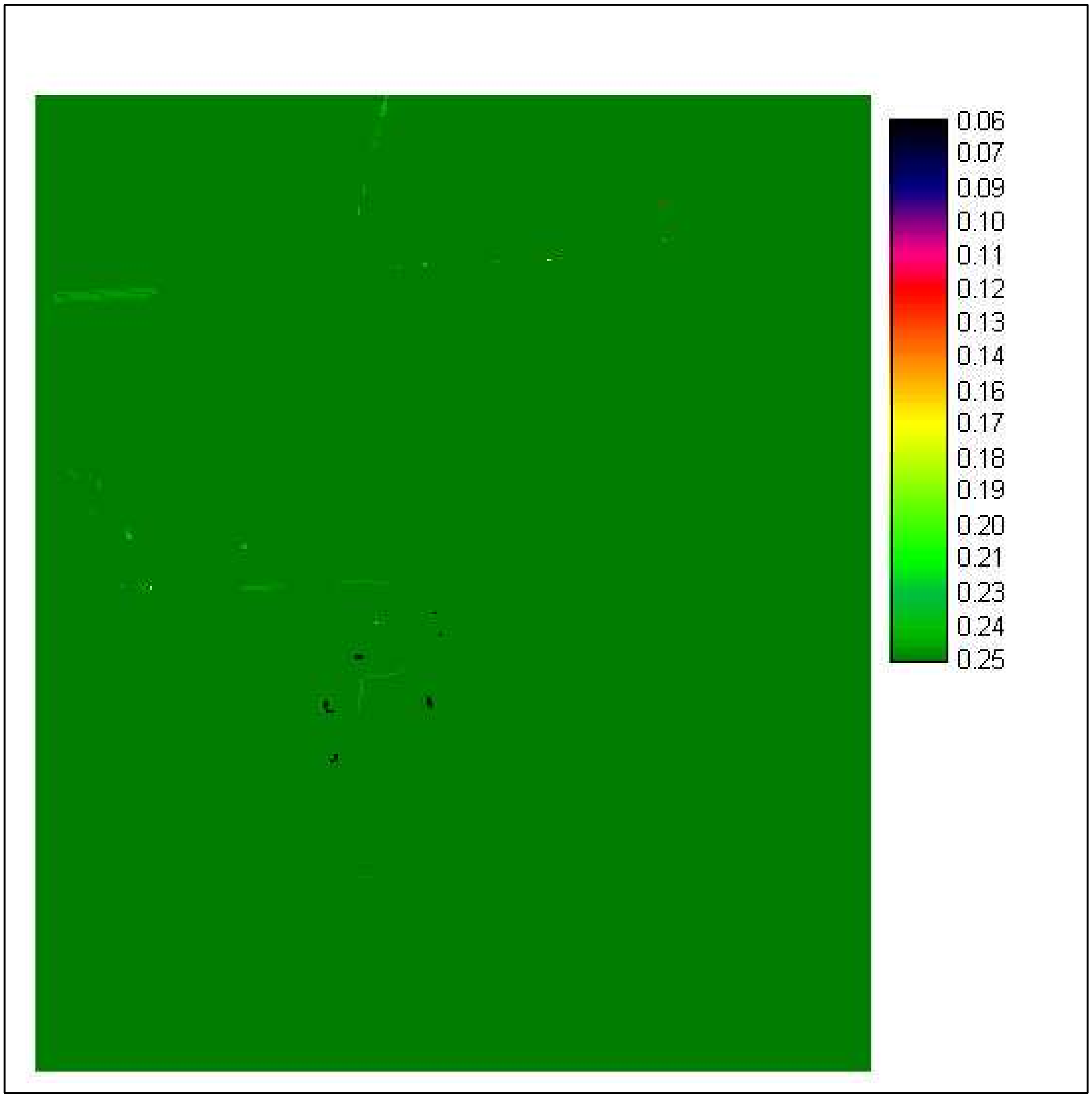

Figure 13: Distance metric image for alternative ‘Floodway 2’ using SCP approach for weight set # 1

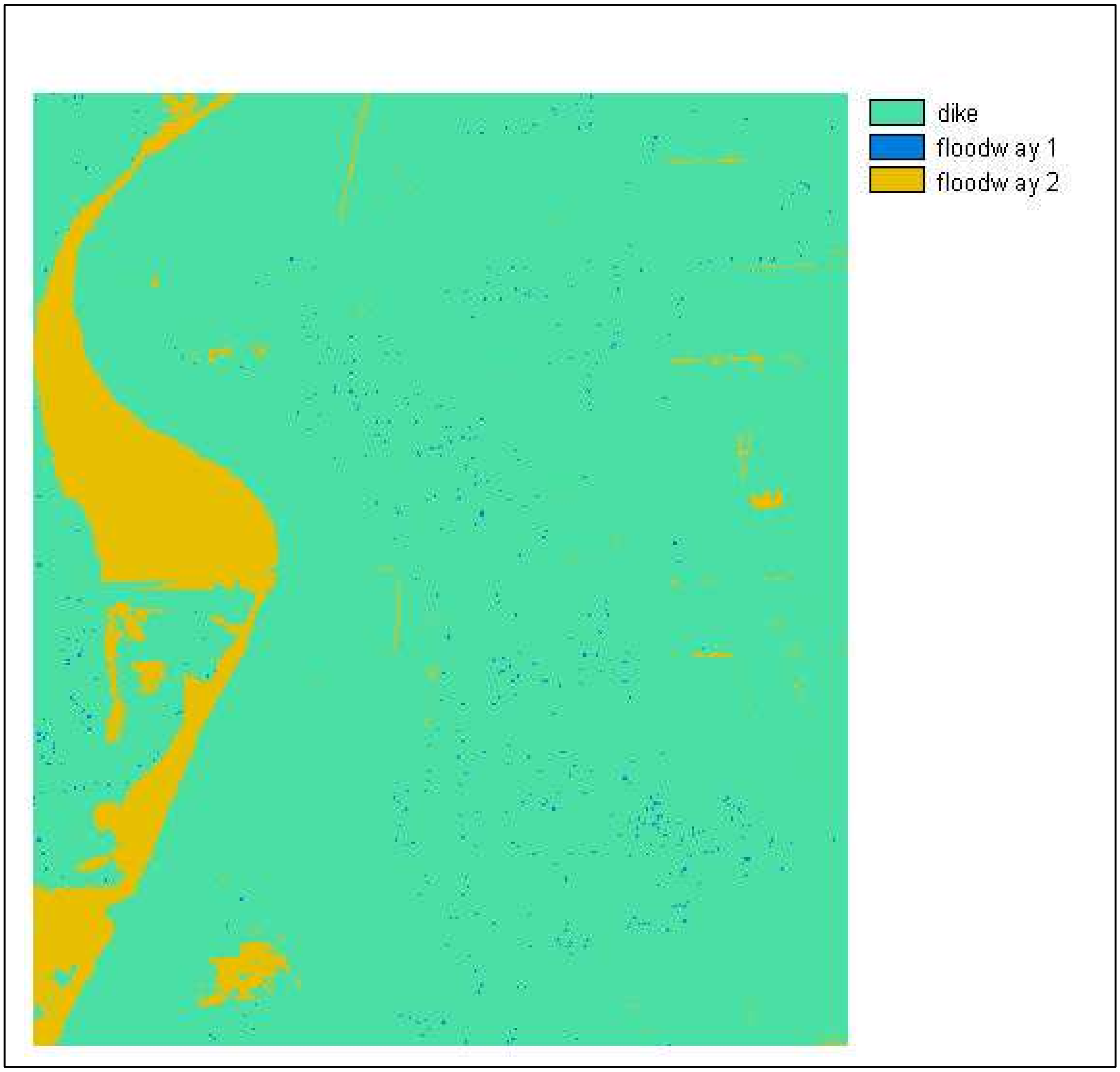

Figure 14: Spatially distributed ranking of three alternatives using SCP approach for weight set # 1.

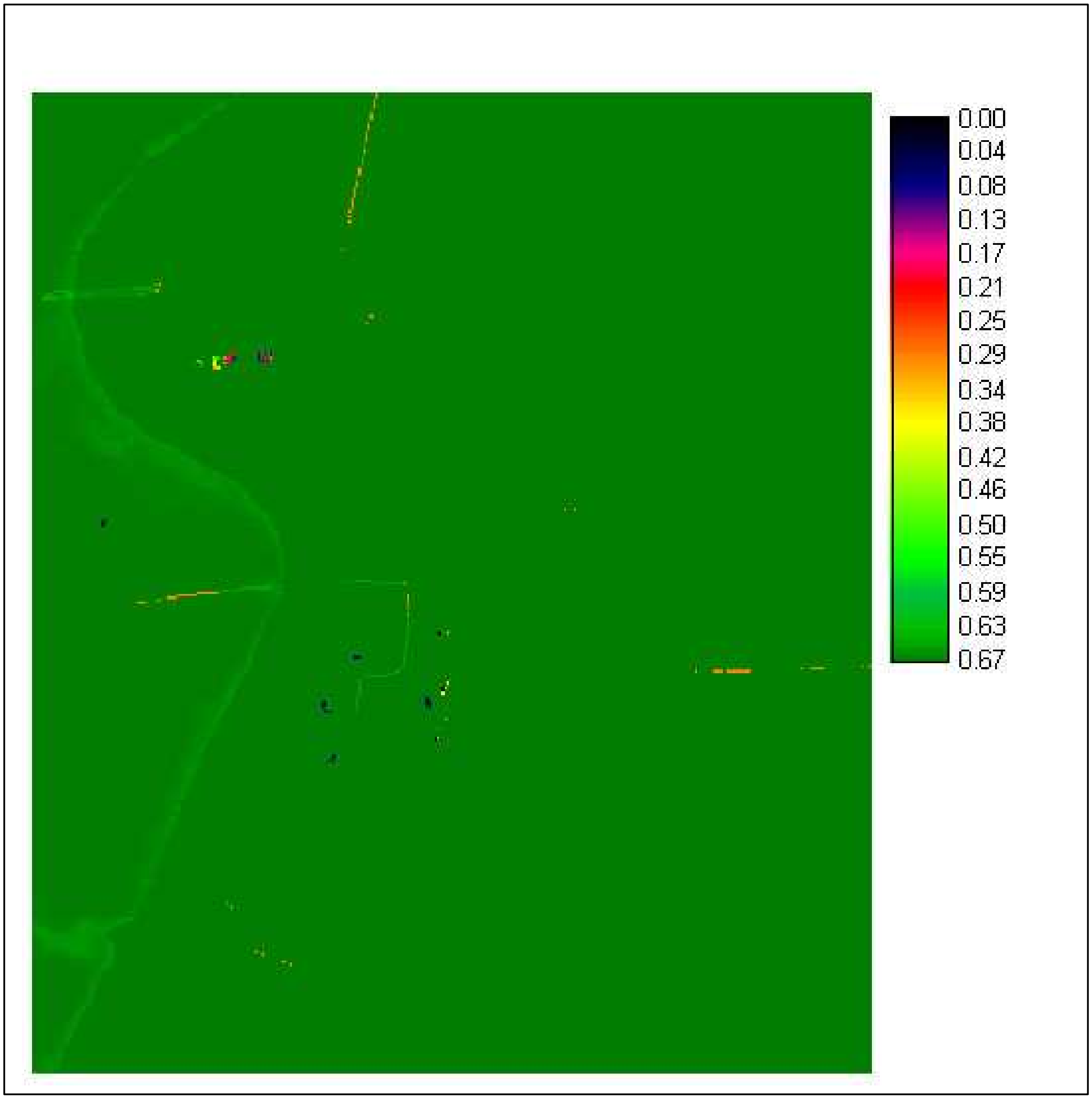

Figure 15: Distance metric image for alternative ‘Dike’ using SCP approach for weight set # 2

Figure 16: Distance metric image for alternative 'Floodway 1' using SCP approach for weight set # 2

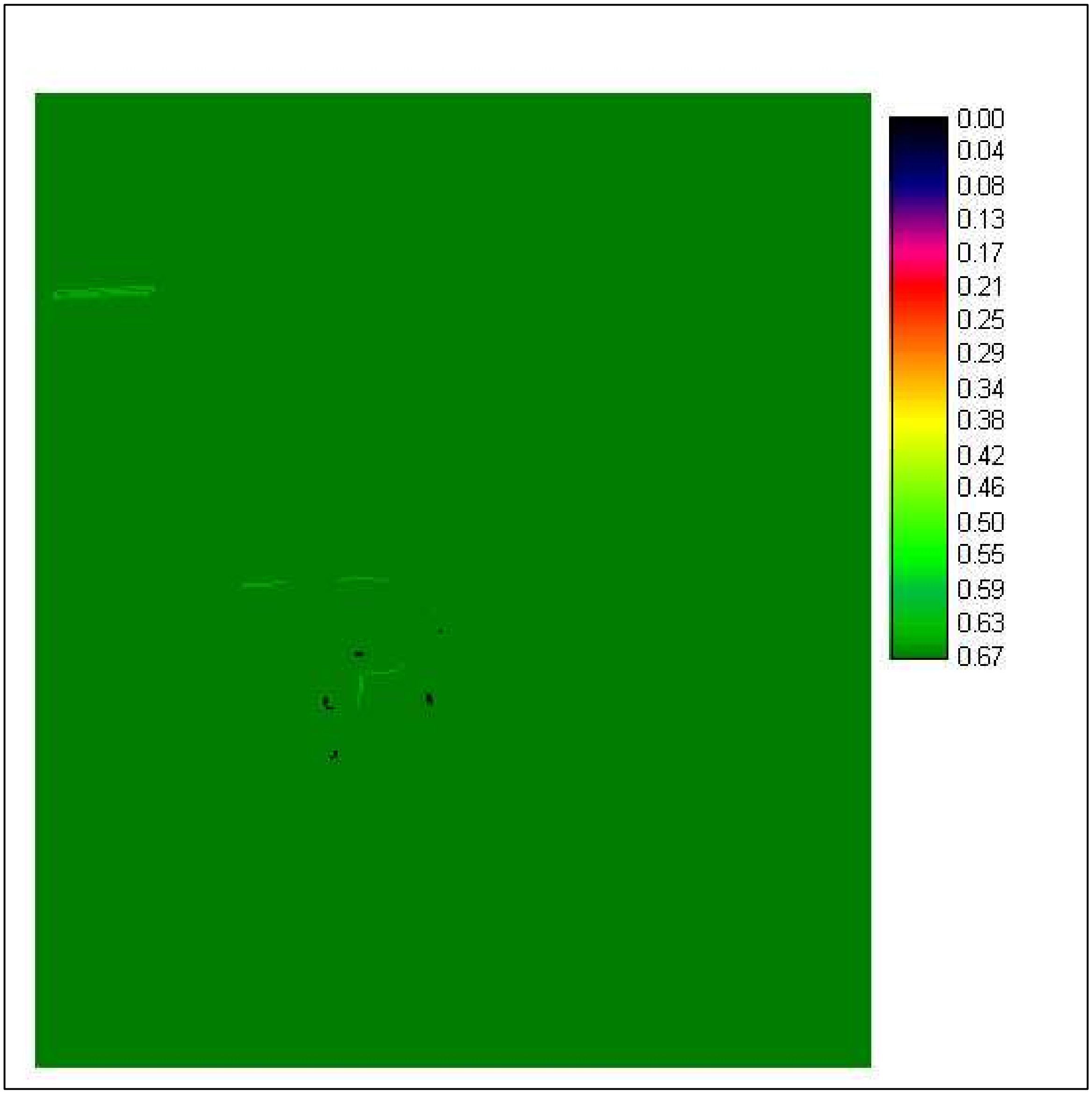

Figure 17: Distance metric image for alternative ‘Floodway 2’ using SCP approach for weight set # 2

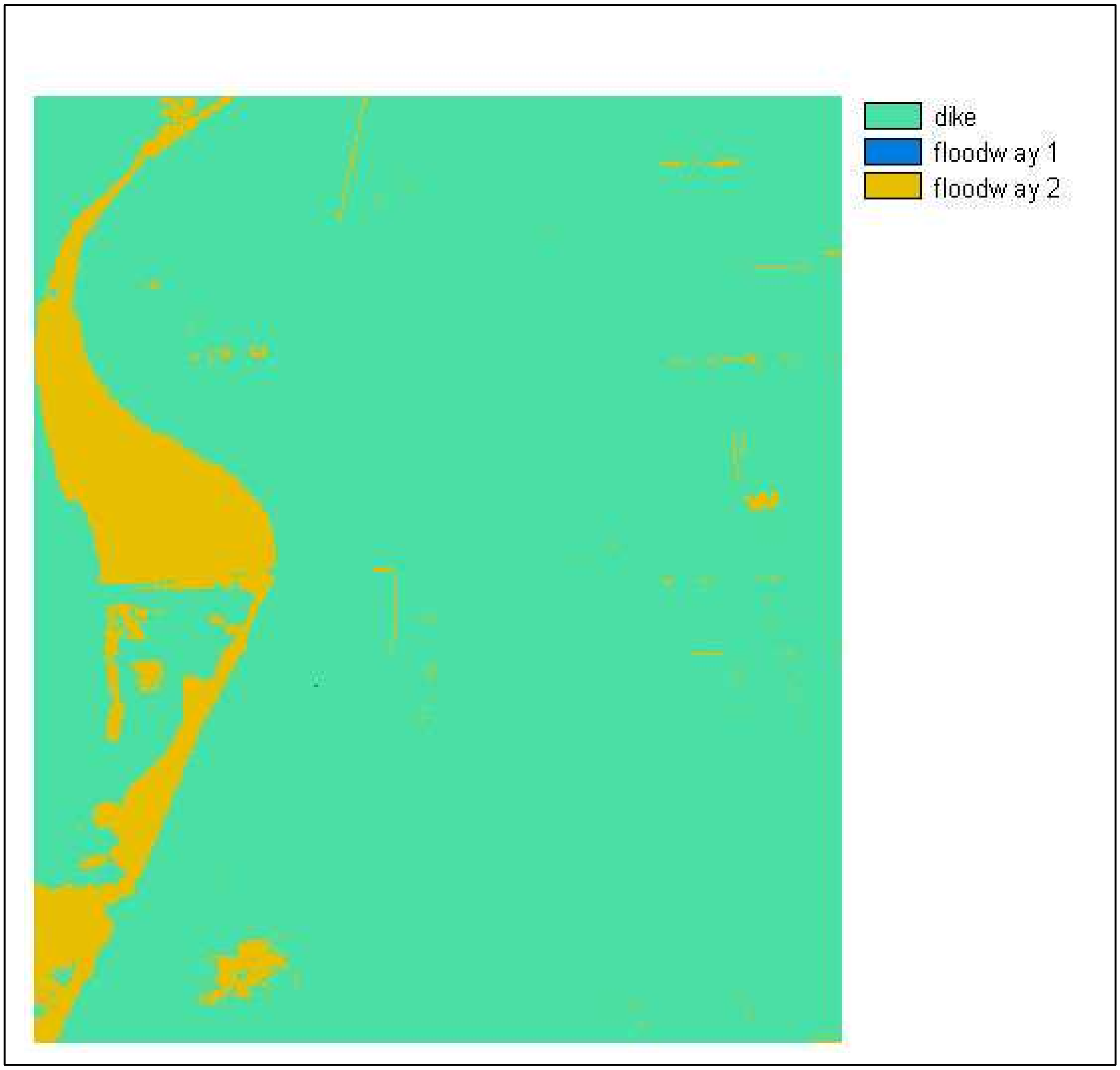

Figure 18: Spatially distributed ranking of three alternatives for weight set#2 using SCP approach.

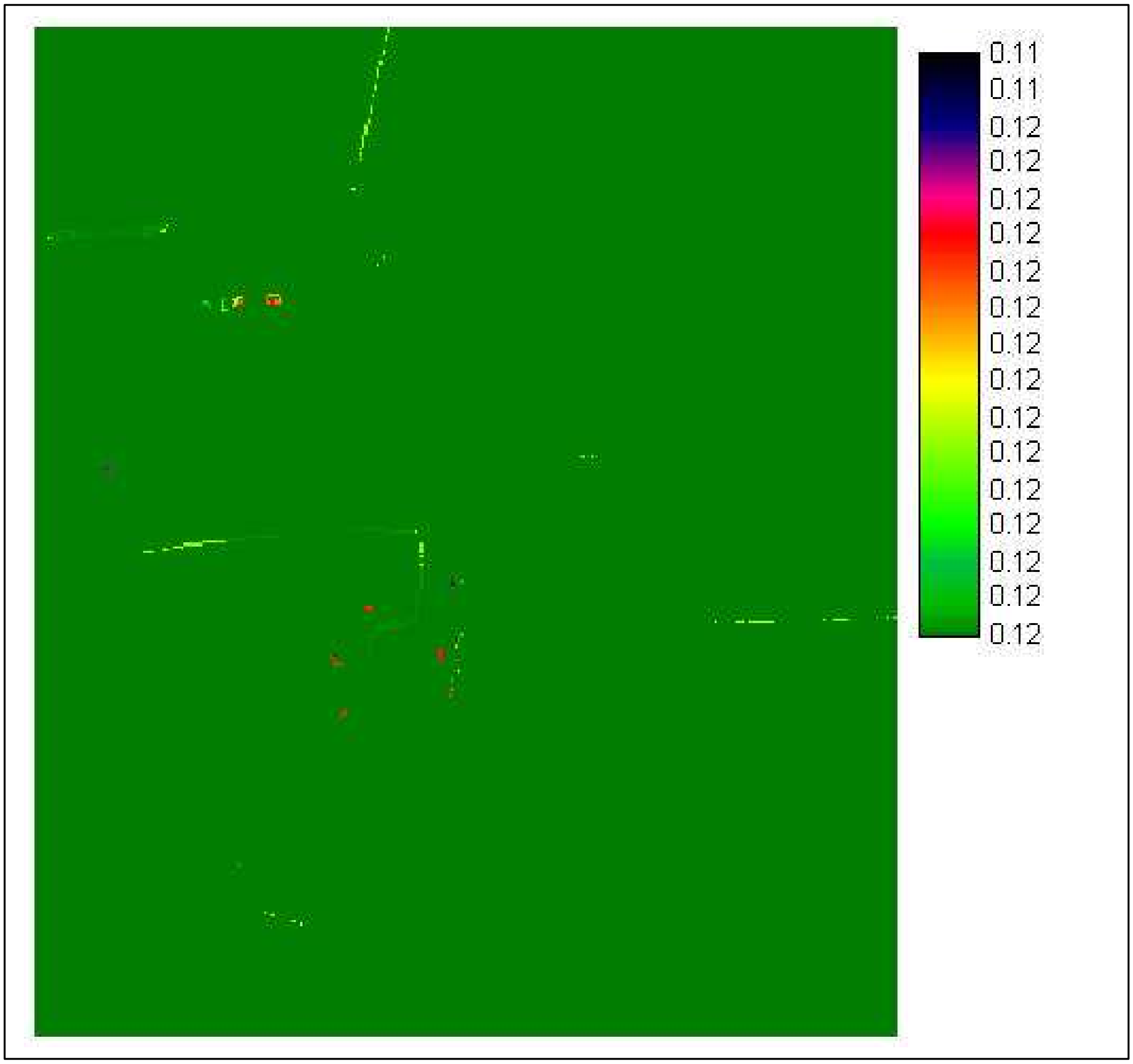

Figure 19: Distance metric image for alternative 'Dike' using SCP approach for weight set # 3

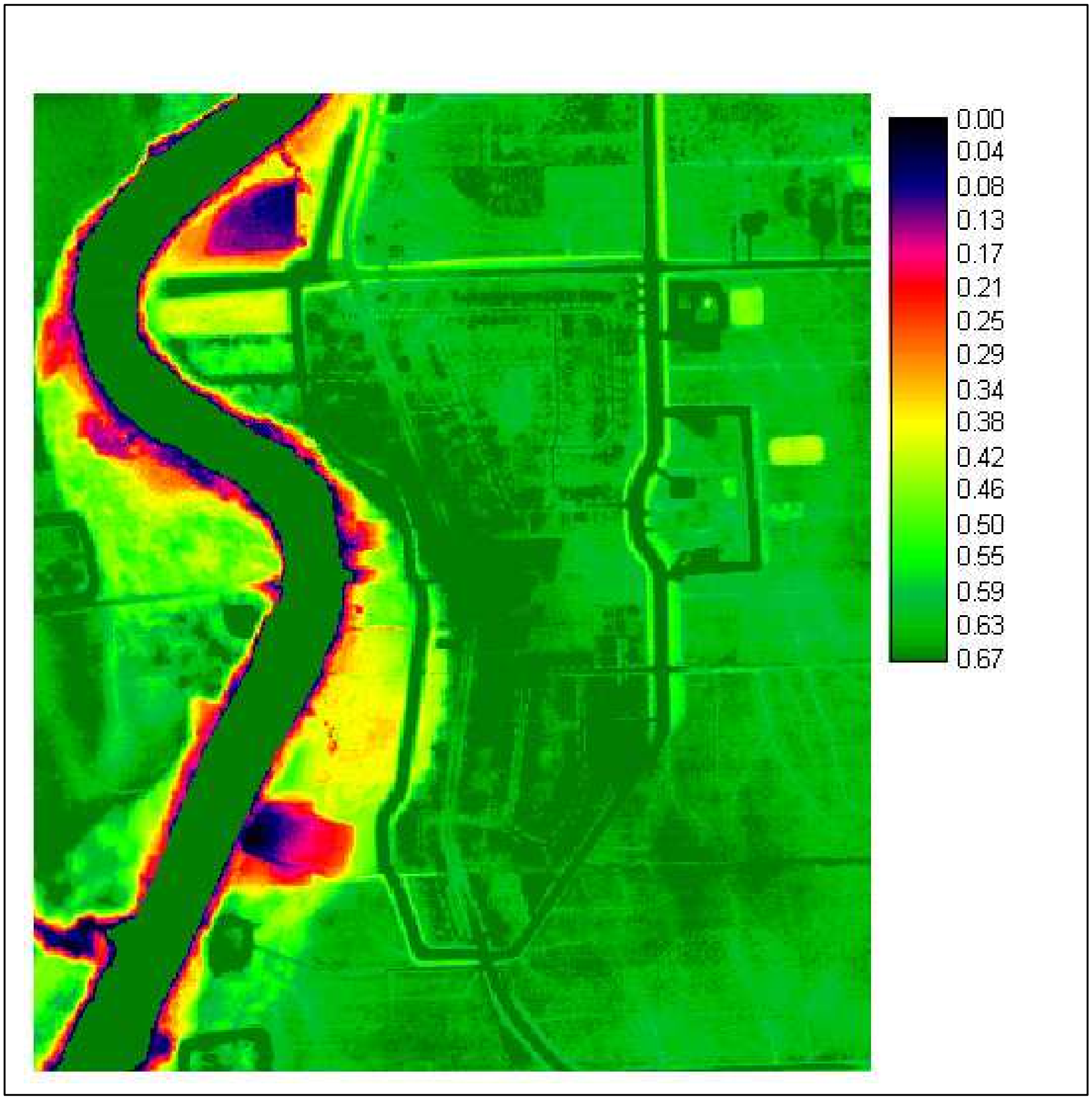

Figure 20: Distance metric image for alternative 'Floodway 1' using SCP approach for weight set # 3

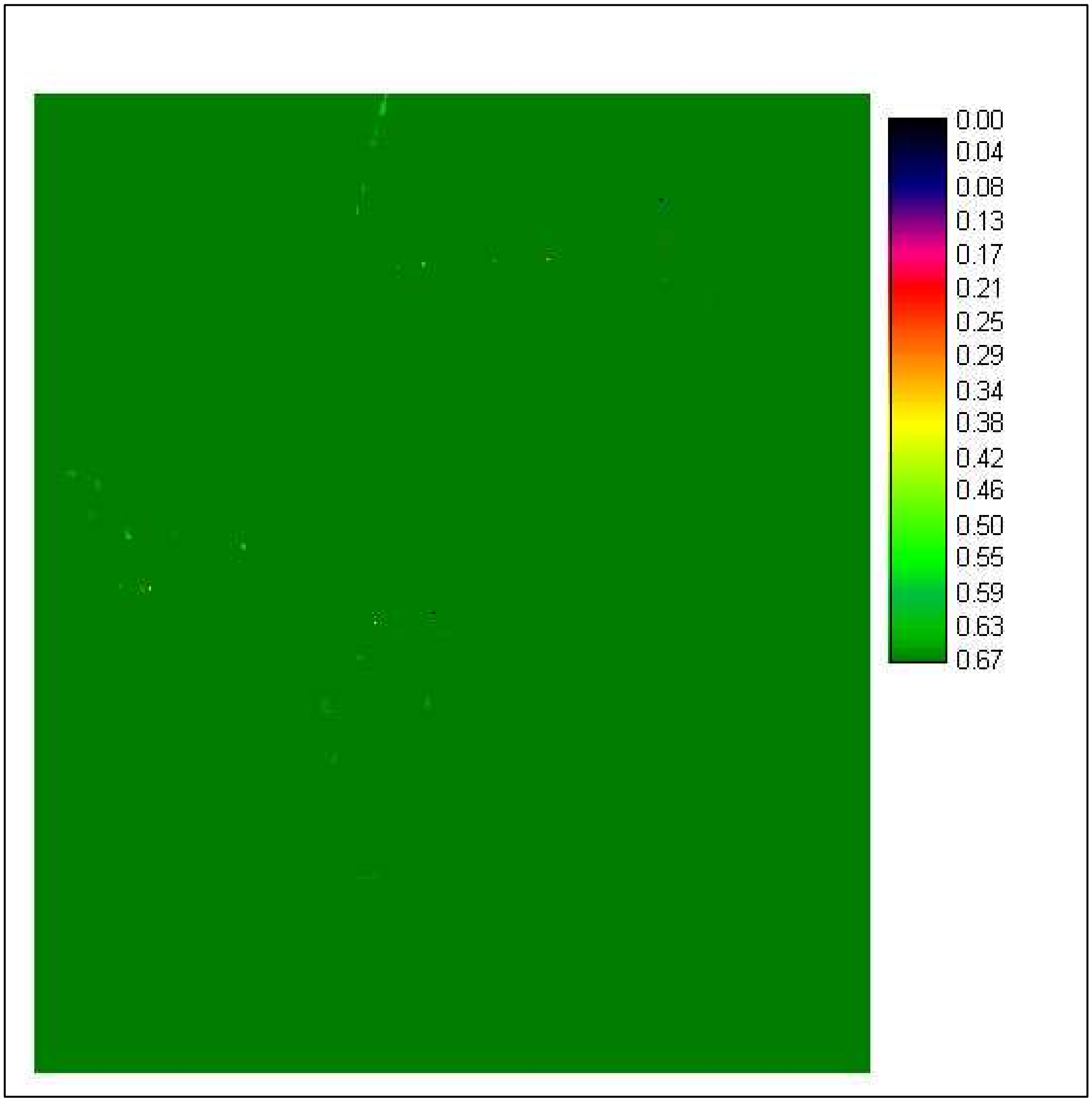

Figure 21: Distance metric image for alternative ‘Floodway 2’ using SCP approach for weight set # 3.

Figure 22: Spatially distributed ranking of three alternatives for weight set # 3 using SCP approach.

3.6 Solution of the Fuzzy Formulation

3.6.1 Fuzzy theory

To account for the uncertainties involved in the process of multi criteria decision making using SCP for flood protection, fuzzy theory has been employed in this study. Basic principles of fuzzy theory are given in Appendix A. By fuzzifying the criteria image inputs the vagueness or uncertainties associated with stakeholders preferences, parameter *p*, and criteria values can be addressed in an efficient and accurate manner. Fuzzification of criteria images is performed using MathWorks' *(www.mathworks.com)* Fuzzy Logic Toolbox in MATLAB (MATLAB, 2000) environment. Selection of suitable membership function is based on the nature of the criteria values (Despic and Simonovic, 2000). In this particular case two membership functions are found to be appropriate and fitting, namely, Triangular membership function (T-MF), which is illustrated in Figure 23, and Z-shaped membership function (Z -MF) as shown in Figure 24.

The principle behind triangular membership function is as follows: triangular curve is a function of a vector, x, and depends on three scalar parameters *a*, *b*, and *c*, as given by

$$f(x:a,b,c)=\begin{Bmatrix} 0, & x\le a \\ \dfrac{x-a}{b-a}, & a\le x\le b \\ \dfrac{c-x}{c-b}, & \mathrm{b}\le \mathrm{x}\le \mathrm{c} \\ 0, & c\le x \end{Bmatrix} \tag{21}$$

The parameters *a* and *b* locate the "feet" of the triangle and the parameter *c* locates the peak as shown in Figure 23. Choice of triangular membership has been made due to its characteristic that this function expands a crisp value on both side of the crisp value to convert the crisp value into a range format. For example, a crisp value of '4' can be converted to a range of '3.5 to 4.5' while keeping the value '4' as peak value. This is fairly convenient way of fuzzifying any number.

Among the other membership functions there are the Gaussian curve membership function (MF); the Bell-shaped MF; the ∏-shaped MF; the product of two Sigmoidally-shaped MF; and the Trapezoidal-shaped MF. However, these MFs are not very much different from triangular membership function in terms of impacts produced by the application of these membership functions.

The Z-shaped function is basically a spline-based function of x. The parameters a and b ($a < b$) locate the extremes of the sloped of the curves (Figure 24). Z-shaped membership function is defined by:

$$Z(x;a,b)=\begin{cases} 0, & \text{for } x \le a. \\ 1-2\left(\dfrac{x-b}{b-a}\right)^2, & \text{for } a < x \le \dfrac{a+b}{2}. \\ 2\left(\dfrac{b-x}{b-a}\right)^2, & \text{for } \dfrac{a+b}{2} < x \le b. \\ 1, & \text{for } b < x. \end{cases} \tag{22}$$

Z-MF takes any crisp value x and expands it according to the shape of membership function, which is defined by parameters a and b. The fuzzified value is always in the form of a decreasing function (maintaining the Z-shape) between one and zero. For this particular application in this study, Z-shaped MF is appropriate because of its shape, which varies from highest value of MF (one) to lowest value of MF (zero). This shape is suitable to both the criteria considered in this study, namely, flood depth and damage because when flood depth is minimum (zero on x-axis) then the degree of membership is highest (one on y-axix) and vice-versa. Similarly, minimum damage provides highest degree of membership, which suits to the particular objective of minimizing the damages in this research.

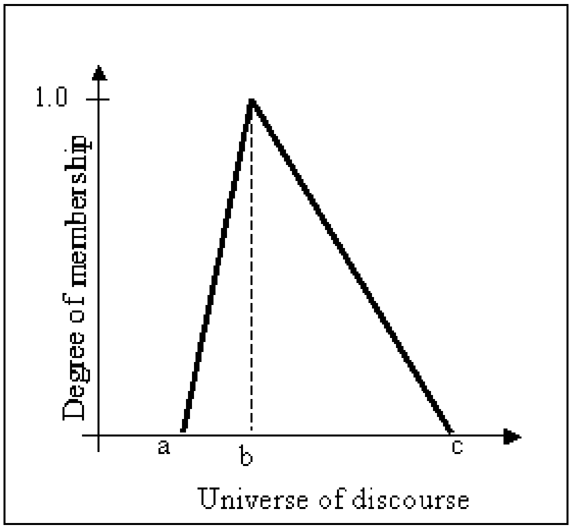

Figure 23: Triangular membership function

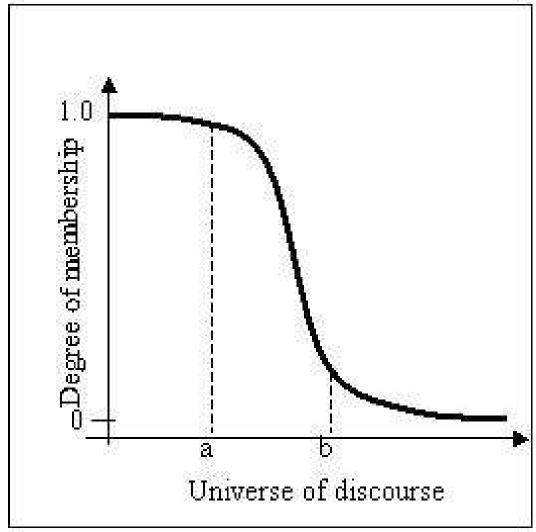

Figure 24: Z-shaped membership

Defuzzification of the fuzzified distance metric is necessary to extract a crisp value that best represents a fuzzy set. In this study defuzzification has been carried out on a cell by cell basis to get the defuzzified value out of fuzzified distance metric values for the entire region of interest. Defuzzification is also a required step for carrying out the ranking of alternatives. Several defuzzification strategies are available in the literature; therefore, selection of suitable method should be made according to the argument type. The variable type can be one of the following:

- Centroid of area method;
- Bisector of area method;
- Mean of maximum method;
- Smallest of maximum method; and
- Largest of maximum method.

In this study, method of Overall Existence Ranking Index (OERI) (Chang and Lee, 1994), which is based on 'centroid of area method', has been applied for defuzzification of fuzzified distance metrics. The choice of this method is based on a study done by Prodanovic and Simonovic (2001), which concluded that OERI method is advantageous over the other methods. MATLAB routine is written to carry out these computations. Equation (22) corresponds to their ranking index.

$$OERI(j) = \int_0^1 \omega(\alpha)\left[\chi_1(\alpha)\mu_{jL}^{-1}(\alpha) + \chi_2(\alpha)\mu_{jR}^{-1}(\alpha)\right]d\alpha \tag{22}$$

where: j stands for alternative j; α represents the degree of membership; $\chi_1(\alpha)$ and $\chi_2(\alpha)$ are functions for subjective weightings; $\omega(\alpha)$ is a parameter to specify a weighting scheme for particular levels of membership; $\mu_{jL}^{-1}(\alpha)$ represents the inverse of the left part; and $\mu_{jR}^{-1}(\alpha)$ is the inverse of the right part of the membership function.

With reference to the Equation (22), it should be noted that $\chi_1(\alpha)$ and $\chi_2(\alpha)$ indicate neutral, optimistic and pessimistic preferences of the decision maker, with the restriction that $\chi_1(\alpha) + \chi_2(\alpha) = 1$. Also, $\omega(\alpha)$, which can specify different weighs for different degree of memberships. In this research it has been taken as one because all degrees of membership are weighed equally.

Linear and non-linear functions for the subjective type weighting are possible, thus giving the user more control in the ranking. For χ_1 values greater than 0.5, the left side of the membership function is weighted more than the right side, which in turn makes the decision maker more optimistic. If the right side is weighted more, the decision maker is considered more of a pessimist. This is because a pessimist prefers larger distance metric values, which means that he/she prefers a solution that is further away from the ideal solution. In summary, the risk preferences are: if $\chi_1 < 0.5$, the user is a pessimist (risk averse); if $\chi_1 = 0.5$, the user is neutral; and if $\chi_1 > 0.5$, the user is an optimist (risk taker).

Simply stated, Chang and Lee's (1994) Overall Existence Ranking Index is a sum of the weighted areas between the membership axis and the left and right inverses of a fuzzy number (Prodanovic and Simonovic, 2002).

Defuzzified distance metric images need to be ranked to arrive at the preferred flood protection alternative on a cell by cell basis. Using GIS software's multi decision making module, ranking process has been completed by providing the defuzzified distance metric images of all the flood protection alternatives and each input images' threshold value. Finally, the spatially distributed ranked alternatives are displayed in a separate image showing alternative preferences in different colors for each location.

Proposed SFCP is implemented to all the three alternatives for three weight sets (Table 2). According to Equation (12), fuzzified images of the best scenario, the worst scenario and the actual criteria are obtained using (i) Triangular membership function (T-MF), and (ii) Z-shaped membership function (Z-MF). MATLAB routines are developed to carry out the fuzzification of input criteria images as well as the fuzzified distance metrics calculation for each of the alternatives. Both triangular and Z-shaped membership functions are applied to same set of input criteria images for the purpose of comparison. The resulting images of the fuzzified distance metric are illustrated in the following sub-sections. MATLAB procedure along with the routines developed is given in Appendix D.

3.6.2 Triangular membership function

The new developed technique of Spatial Fuzzy Compromise Programming (SFCP) using triangular membership function (T-MF) is implemented and distance metric images are obtained for all the three sets of weights (Table 2). Ranking of the alternatives has also been arrived at and shown in the figures that follow. Distance metric values for alternatives 'Dike', Floodway 1' and 'Floodway 2' and weight set # 1 are shown in Figures 25 - 27 respectively and Figure 28 shows the ranking of the three alternatives.

The three alternatives' distance metric images for weight set # 2 are given in Figures 29 - 31, and Figure 32 illustrates the ranking for the three alternatives for weight set # 2. Figures 33 – 35 are distance metrics for 'Dike', 'Floodway 1' and 'Floodway 2' for weight set # 3. Ranking of alternatives for weight set # 3 is given in Figure 36.

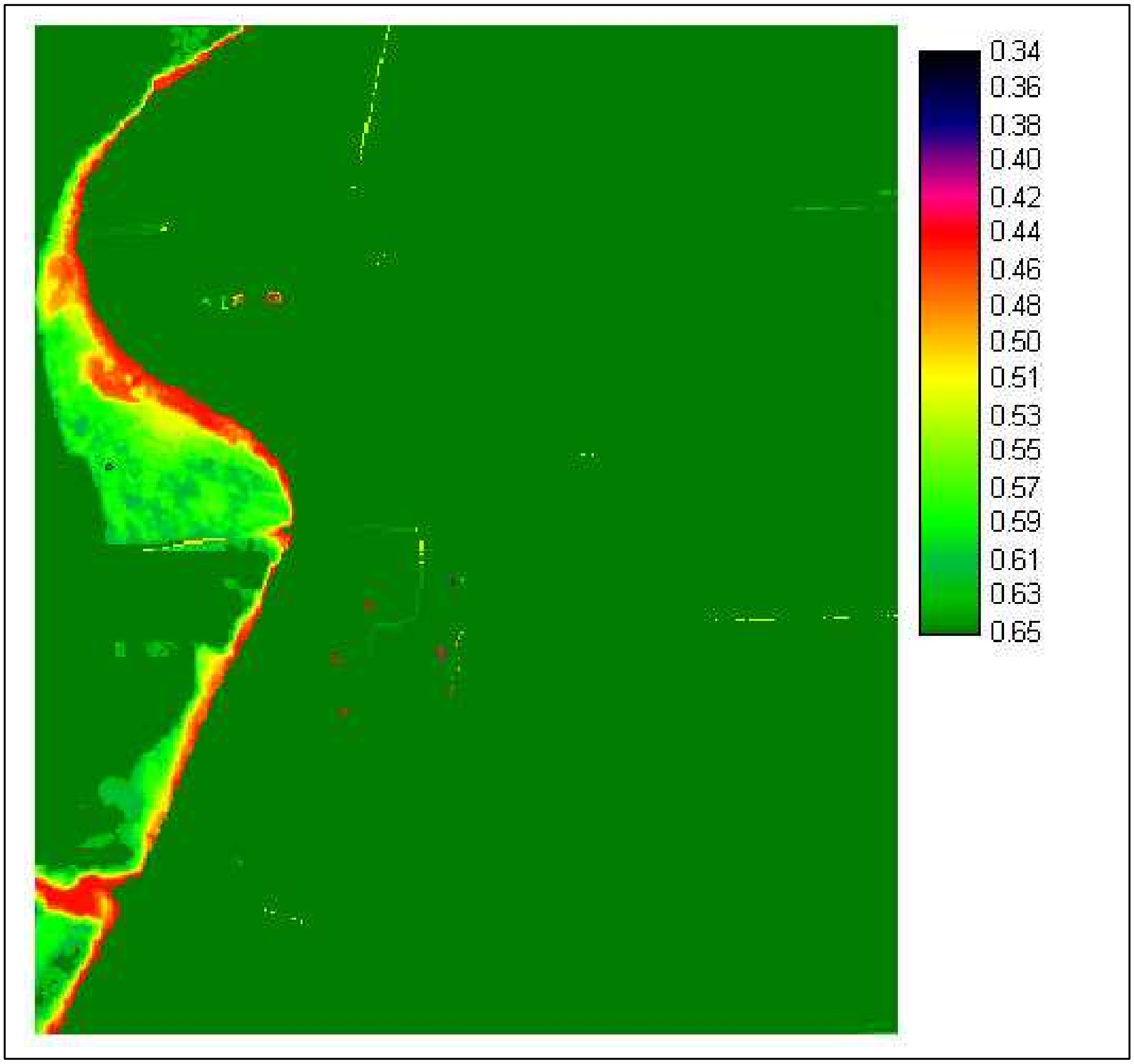

Figure 25: Distance metric image for alternative 'Dike' using SFCP (T-MF) approach for weight set # 1.

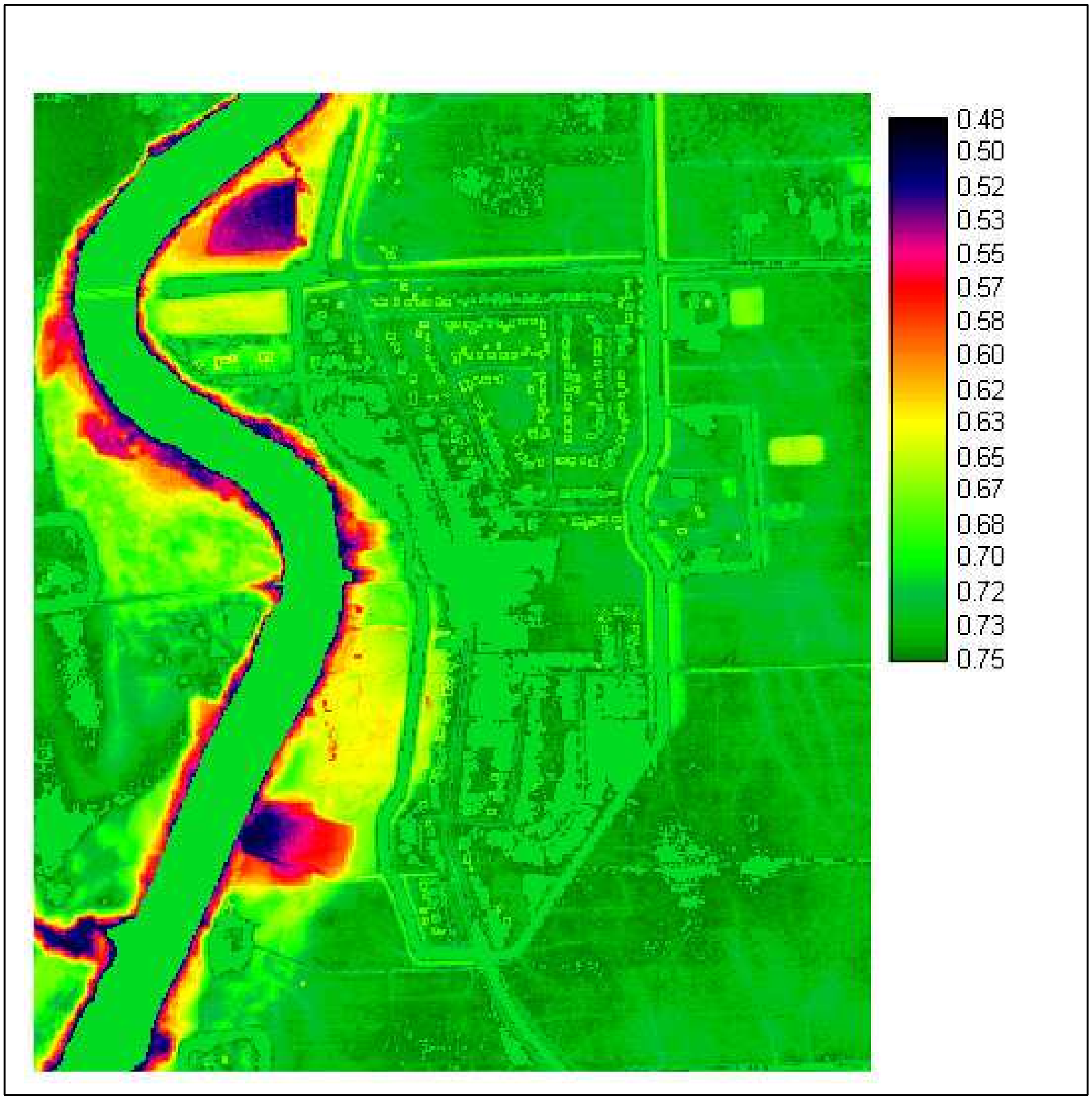

Figure 26: Distance metric image for alternative 'Floodway 1' using SFCP (T-MF) approach for weight set # 1.

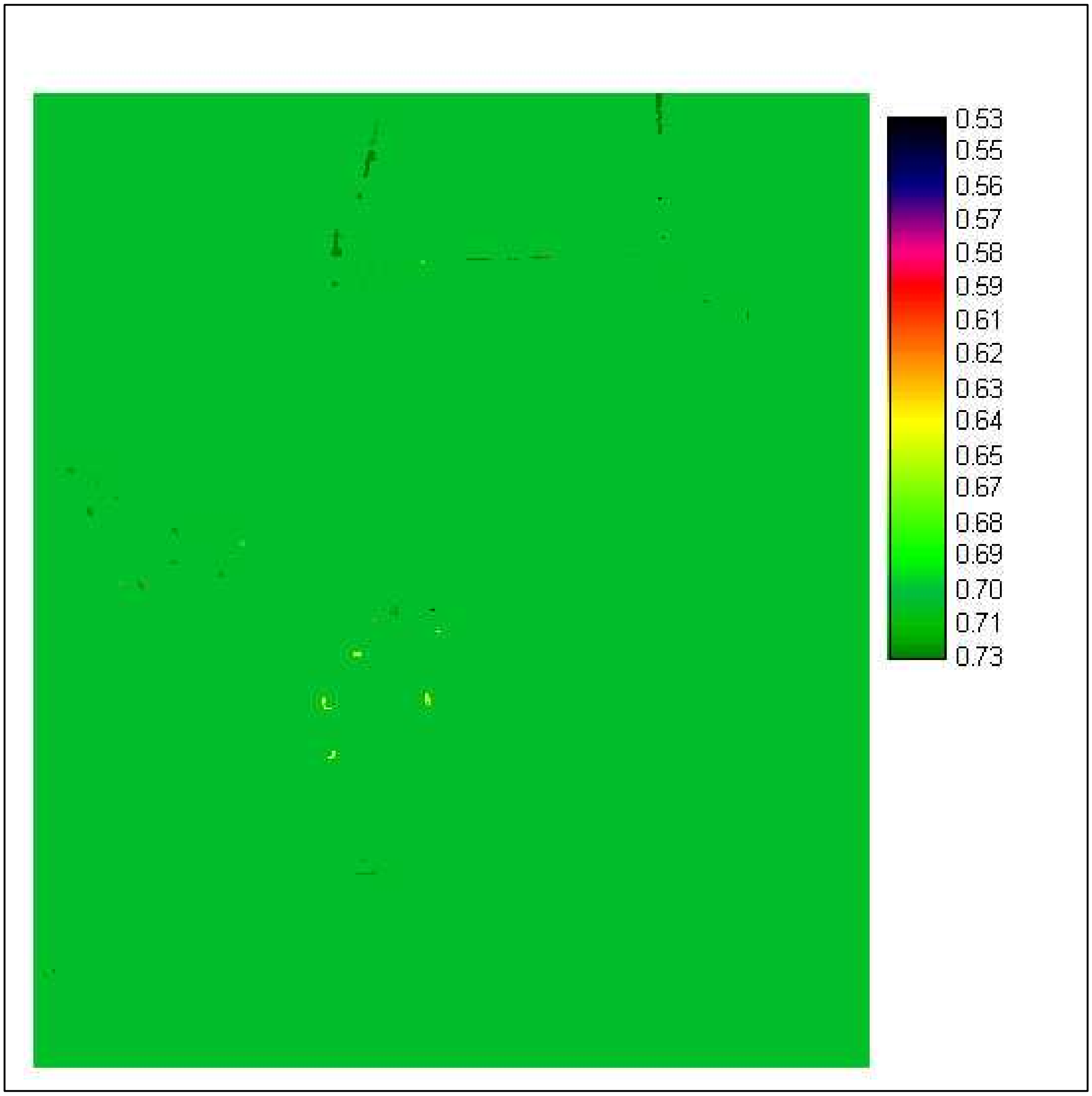

Figure 27: Distance metric image for alternative ‘Floodway 2’ using SFCP (T-MF) approach for weight set # 1.

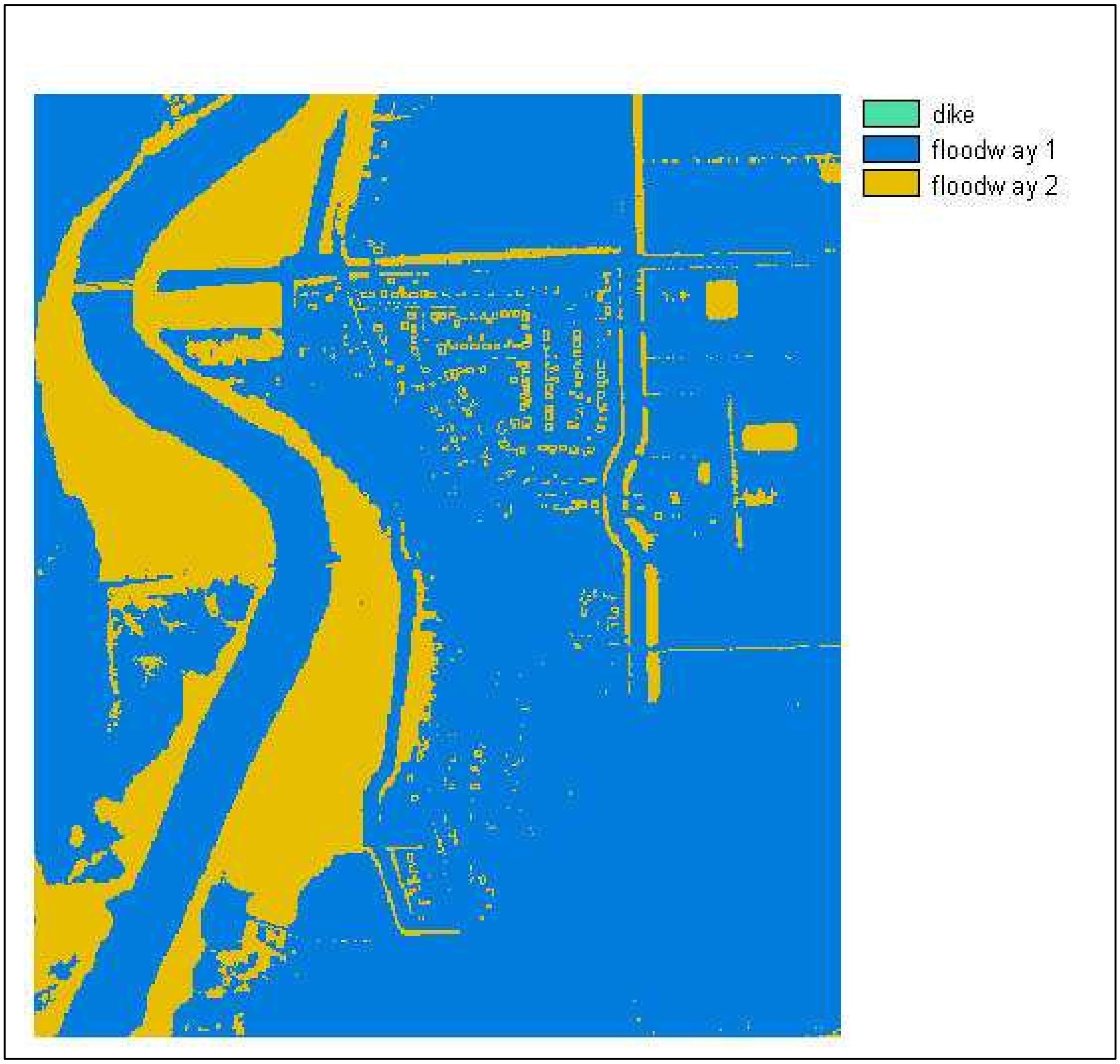

Figure 28: Spatially distributed ranking of three alternatives for weight set # 1 using SFCP (T-MF) approach.

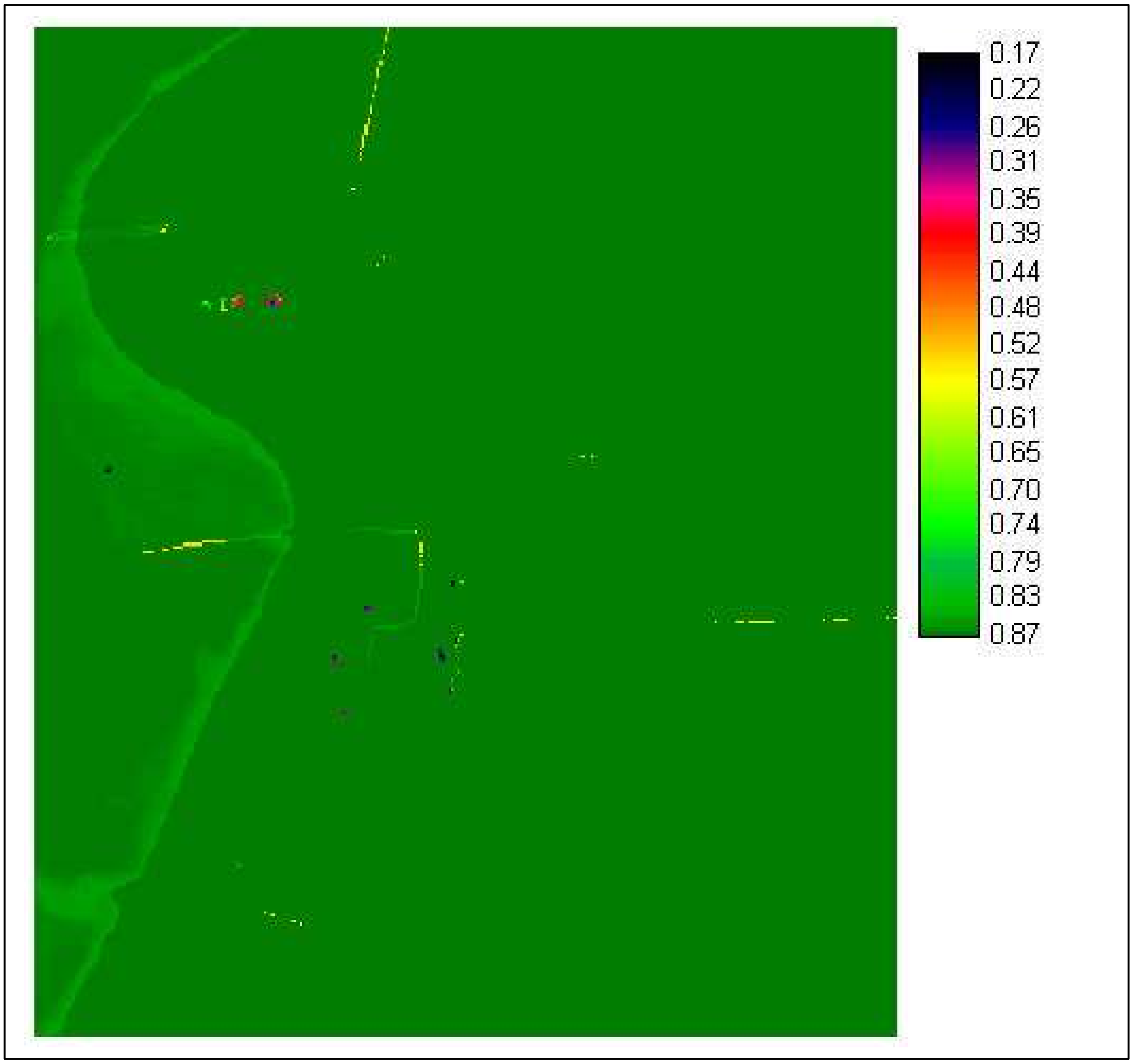

Figure 29: Distance metric image for alternative 'Dike' using SFCP (T-MF) approach for weight set # 2.

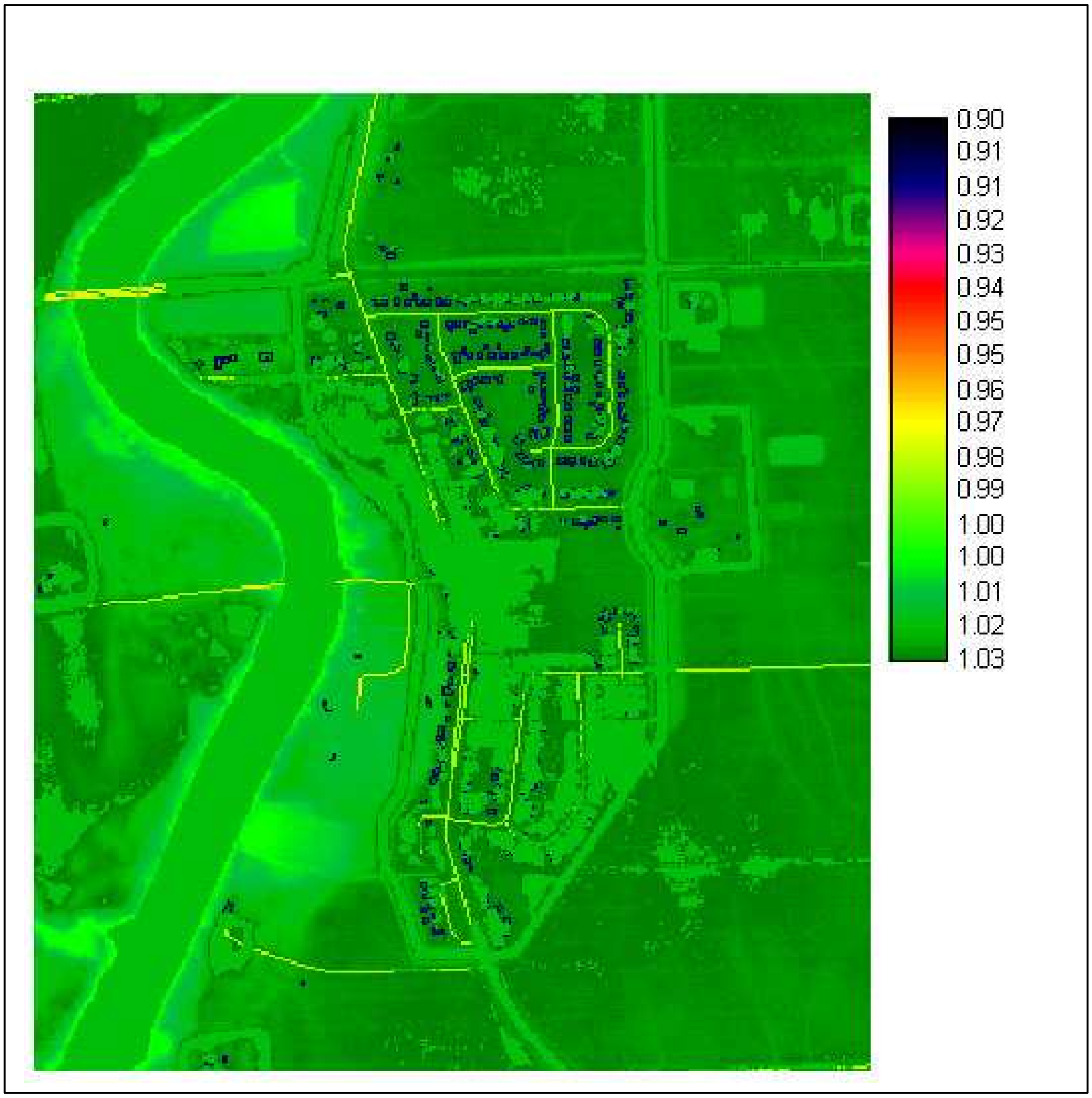

Figure 30: Distance metric image for alternative 'Floodway 1' using SFCP (T-MF) approach for weight set # 2.

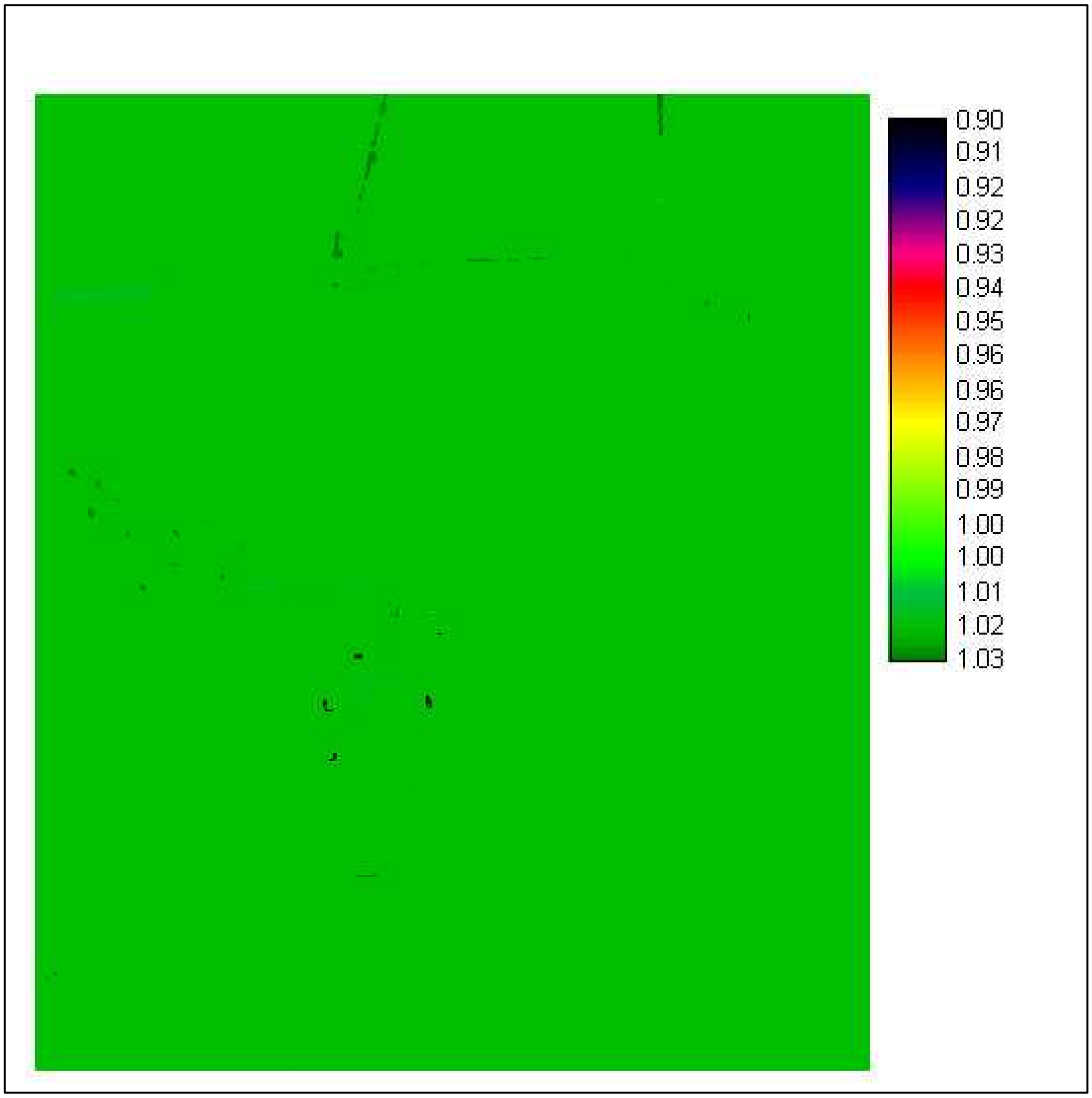

Figure 31: Distance metric image for alternative 'Floodway 2' using SFCP (T-MF) approach for weight set # 2.

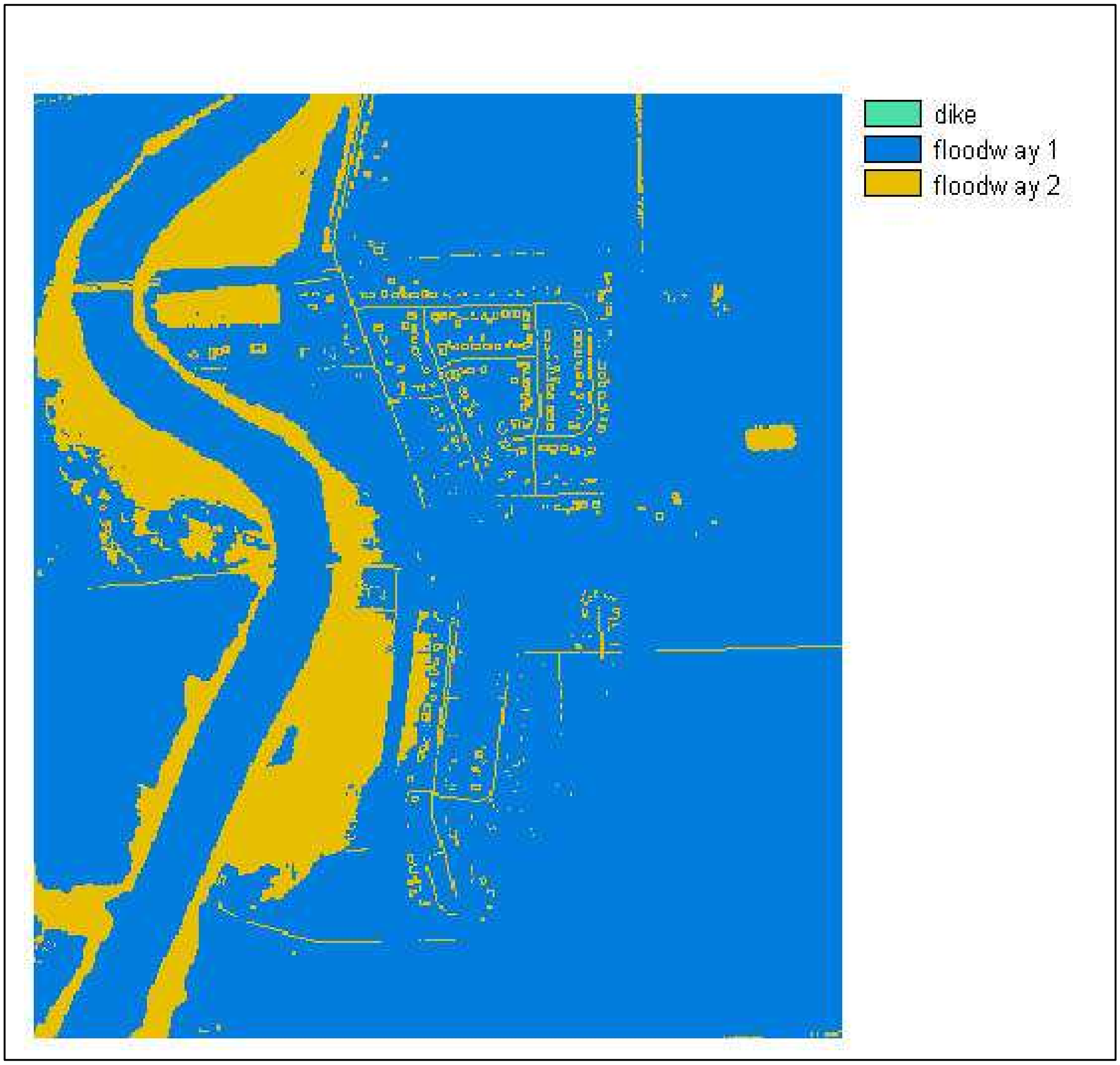

Figure 32: Spatially distributed ranking of three alternatives for weight set # 2 using SFCP (T-MF) approach.

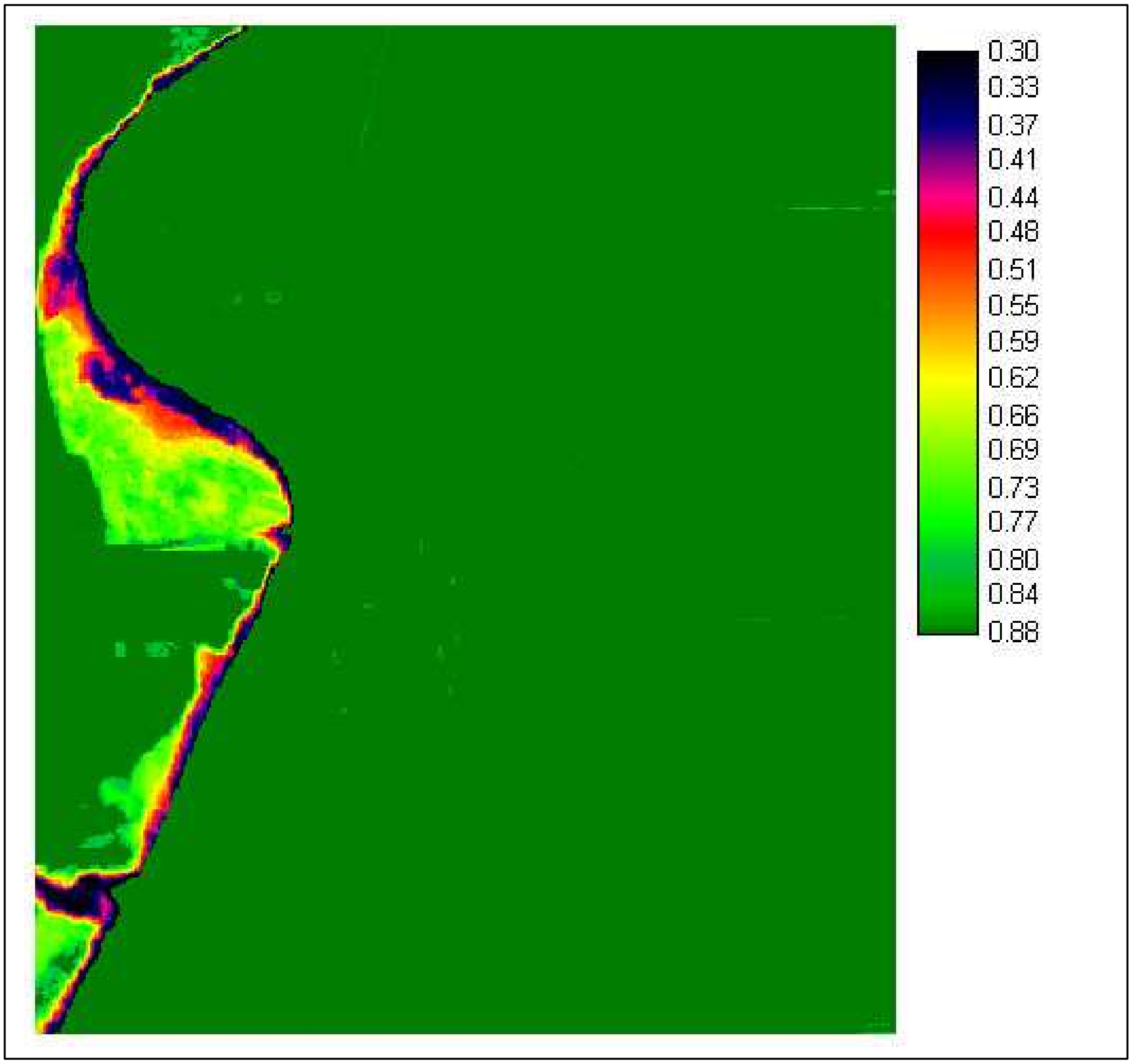

Figure 33: Distance metric image for alternative 'Dike' using SFCP (T-MF) approach for weight set # 3.

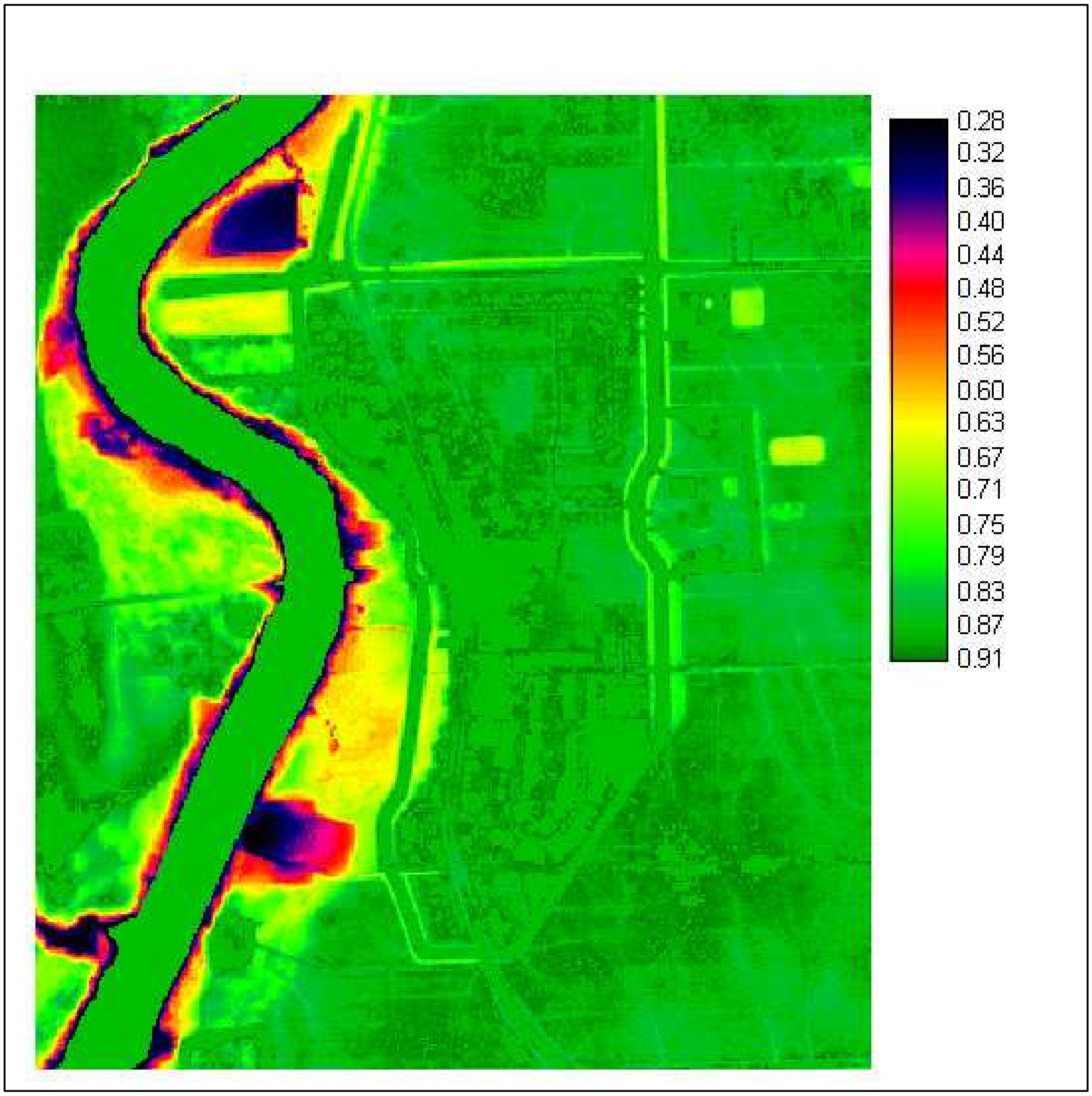

Figure 34: Distance metric image for alternative ‘Floodway 1’ using SFCP (T-MF) approach for weight set # 3.

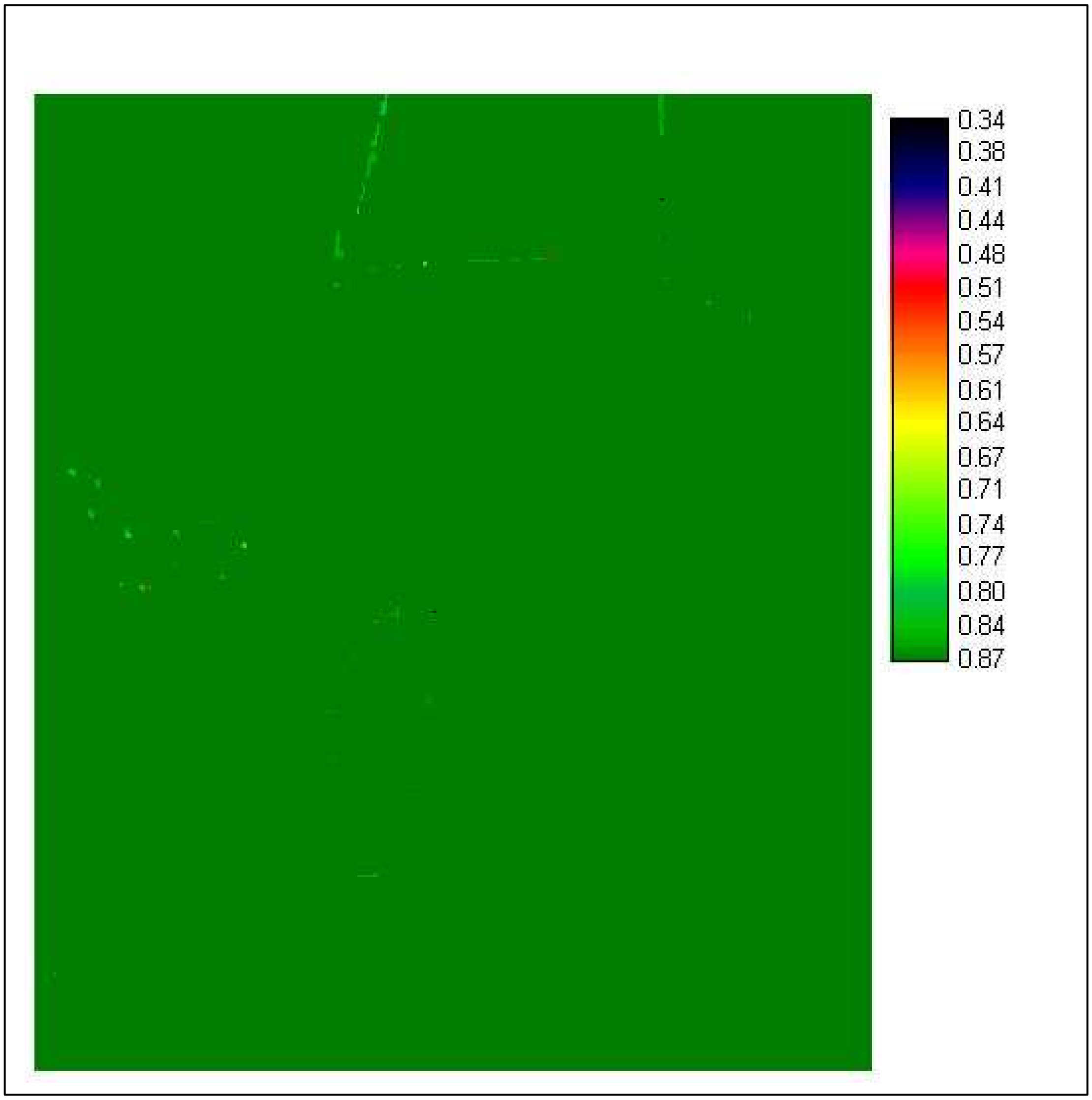

Figure 35: Distance metric image for alternative 'Floodway 2' using SFCP (T-MF) approach for weight set # 3.

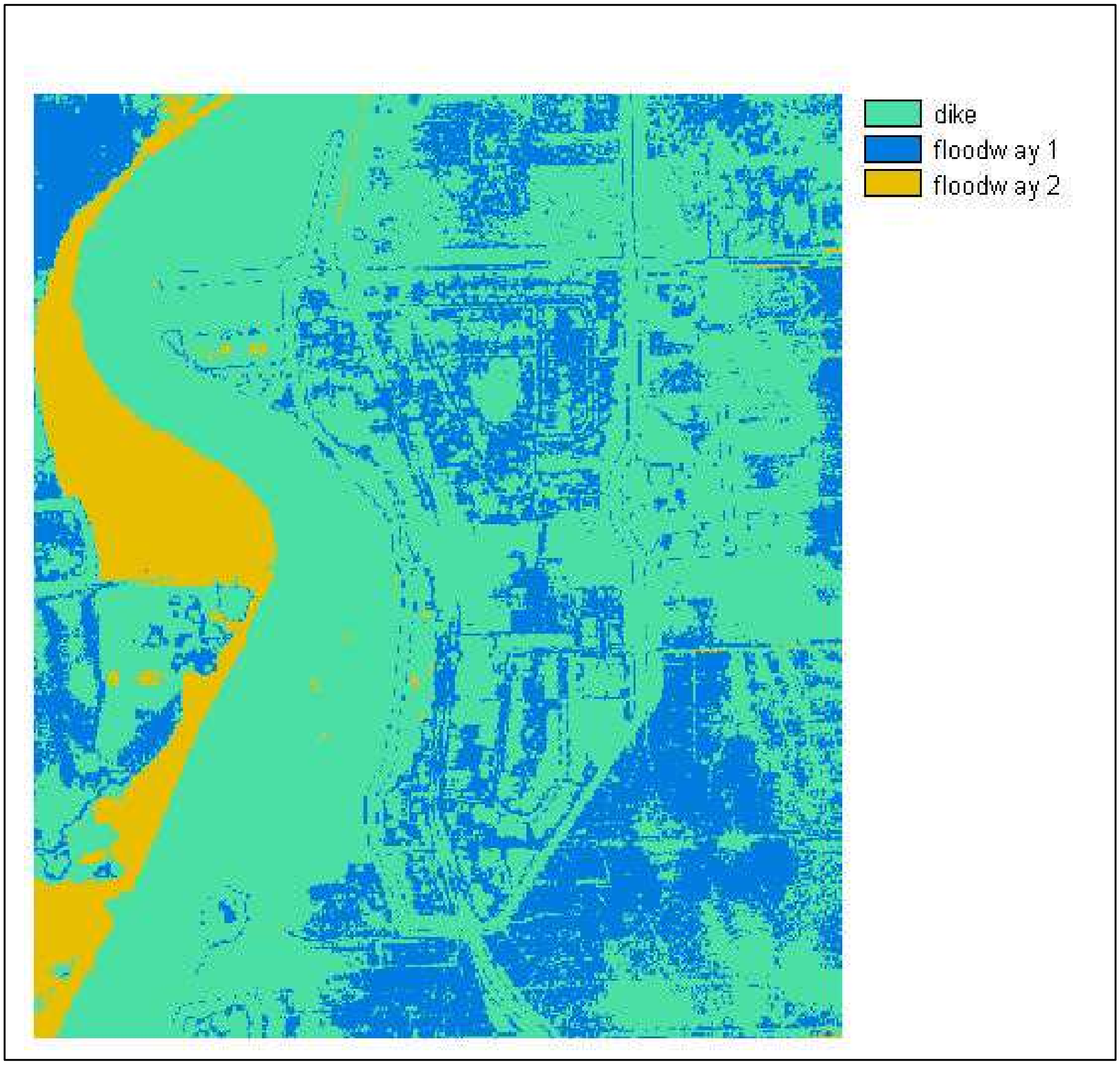

Figure 36: Spatially distributed ranking of three alternatives for weight set # 3 using SFCP (T-MF) approach.

3.6.3 Z-shaped membership function

From the implementation of new proposed MCDM technique of Spatial Fuzzy Compromise Programming (SFCP) using Z-shaped membership function (Z-MF), the distance metric images shown in Figures 37 to 48 for all the three sets of weights are obtained for all the three sets of weights (Table 2). Ranking of the alternatives has also been arrived at and shown in the figures that follow. Distance metric values for alternatives 'Dike', Floodway 1' and 'Floodway 2' and weight set # 1 are shown in Figures 37 - 39 respectively and Figure 40 shows the ranking of the three alternatives. The three alternatives' distance metric images for weight set # 2 are given in Figures 41 - 43, and Figure 44 illustrates the ranking for the three alternatives for weight set # 2. Figures 45 – 47 are distance metrics for 'Dike', 'Floodway 1' and 'Floodway 2' for weight set # 3. Ranking of alternatives for weight set # 3 is given in Figure 48.

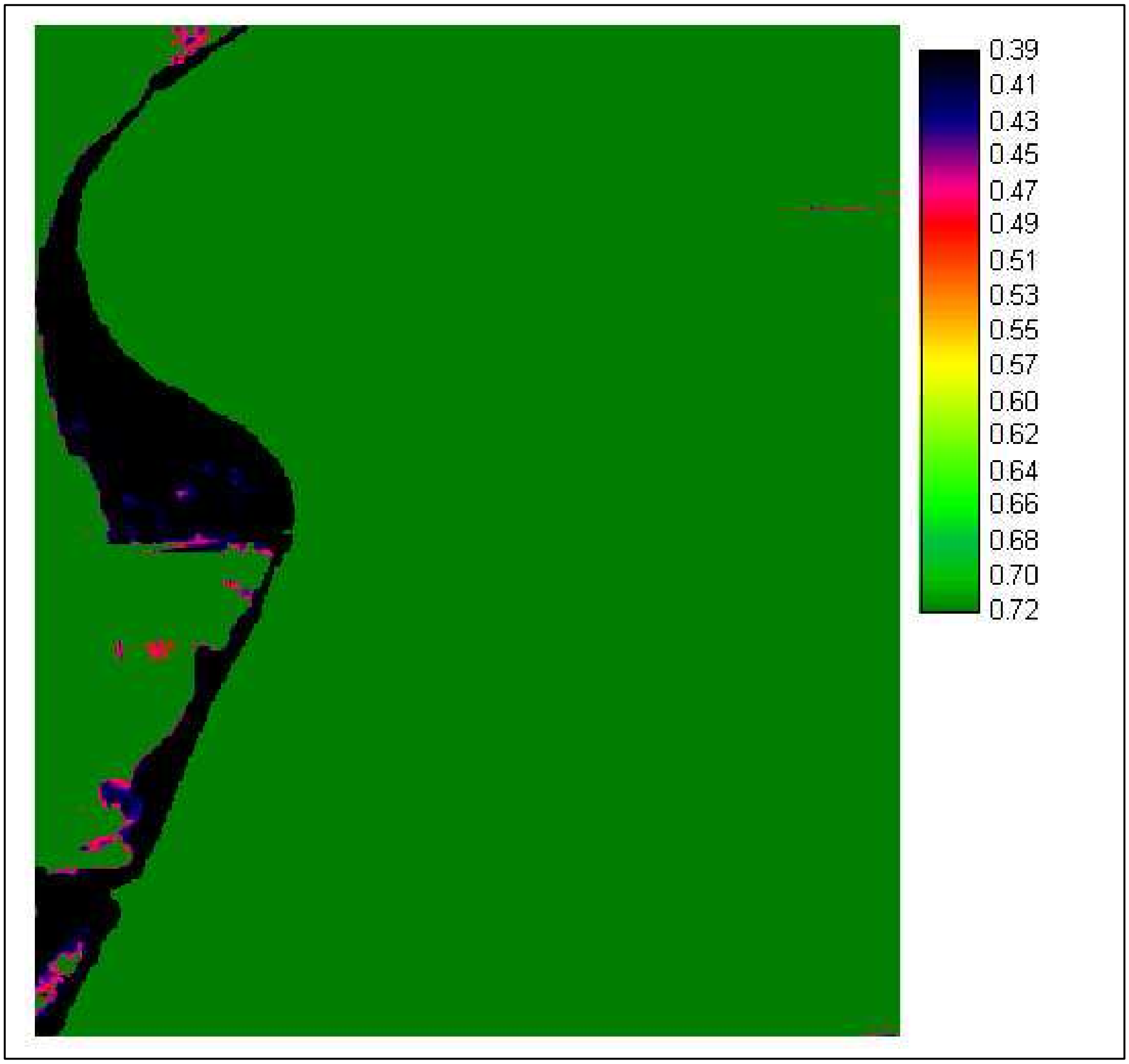

Figure 37: Distance metric image for alternative 'Dike' using SFCP (Z-MF) approach for weight set # 1.

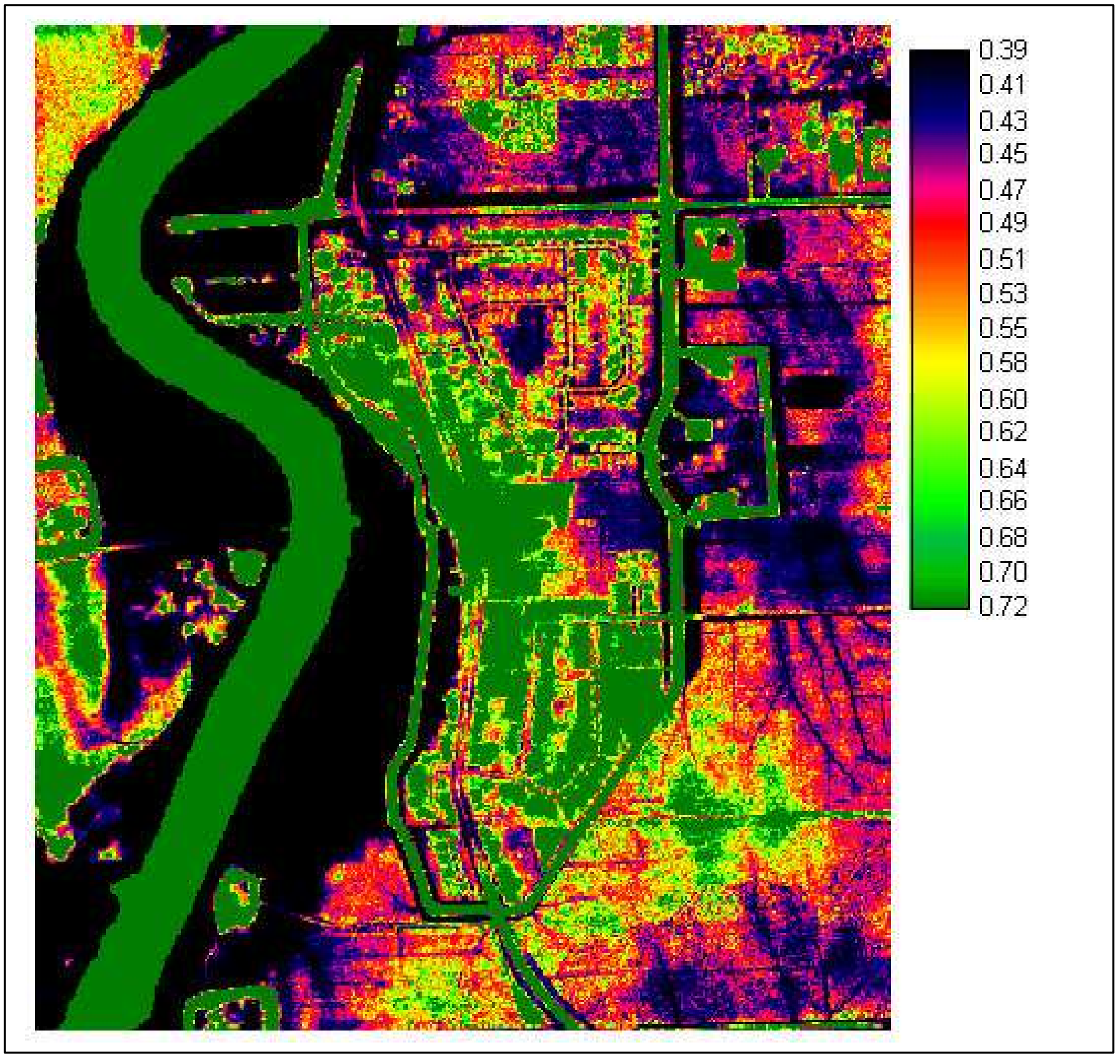

Figure 38: Distance metric image for alternative ‘Floodway 1’ using SFCP (Z-MF) approach for weight set # 1.

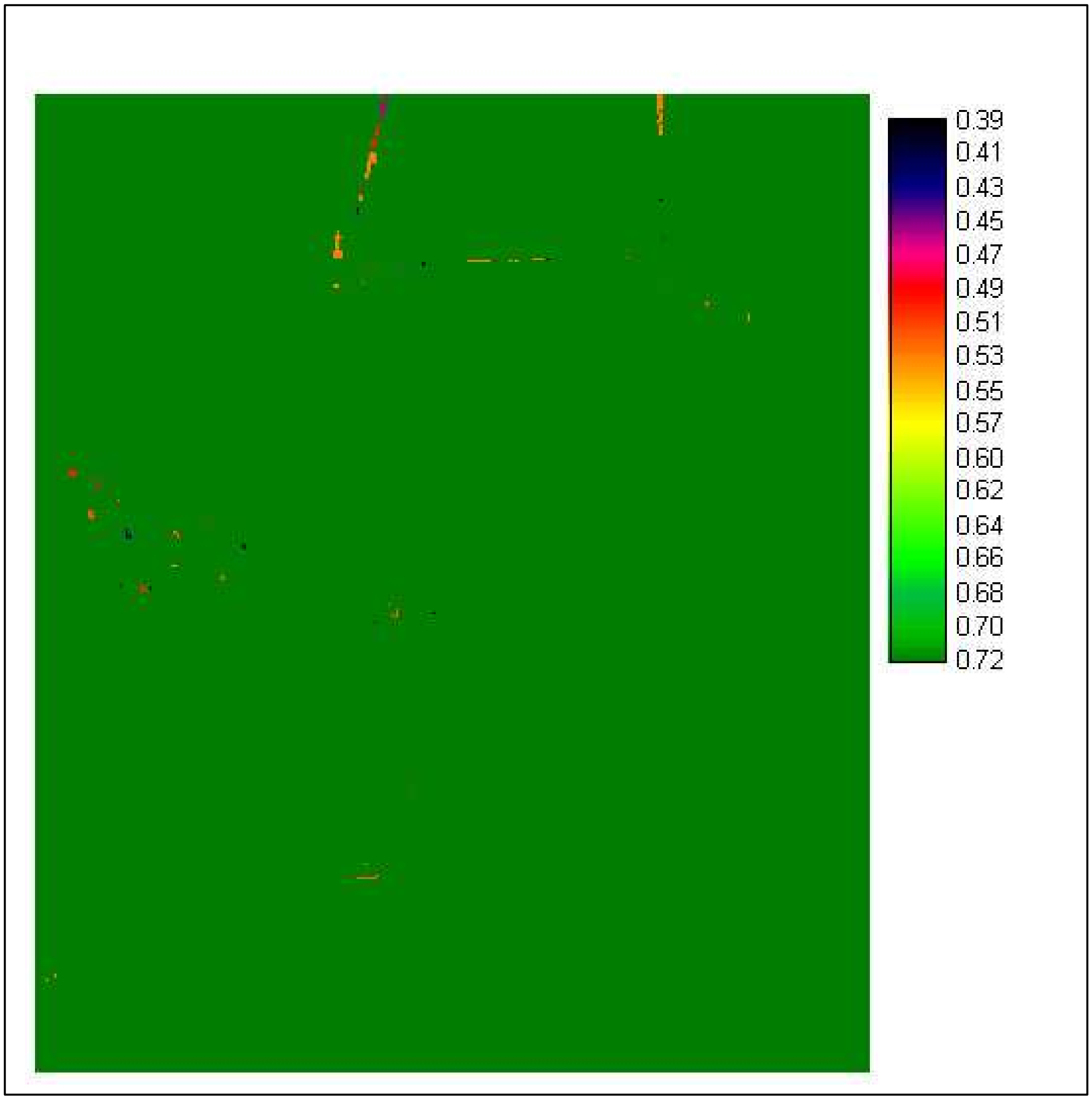

Figure 39: Distance metric image for alternative 'Floodway 2' using SFCP (Z-MF) approach for weight set # 1.

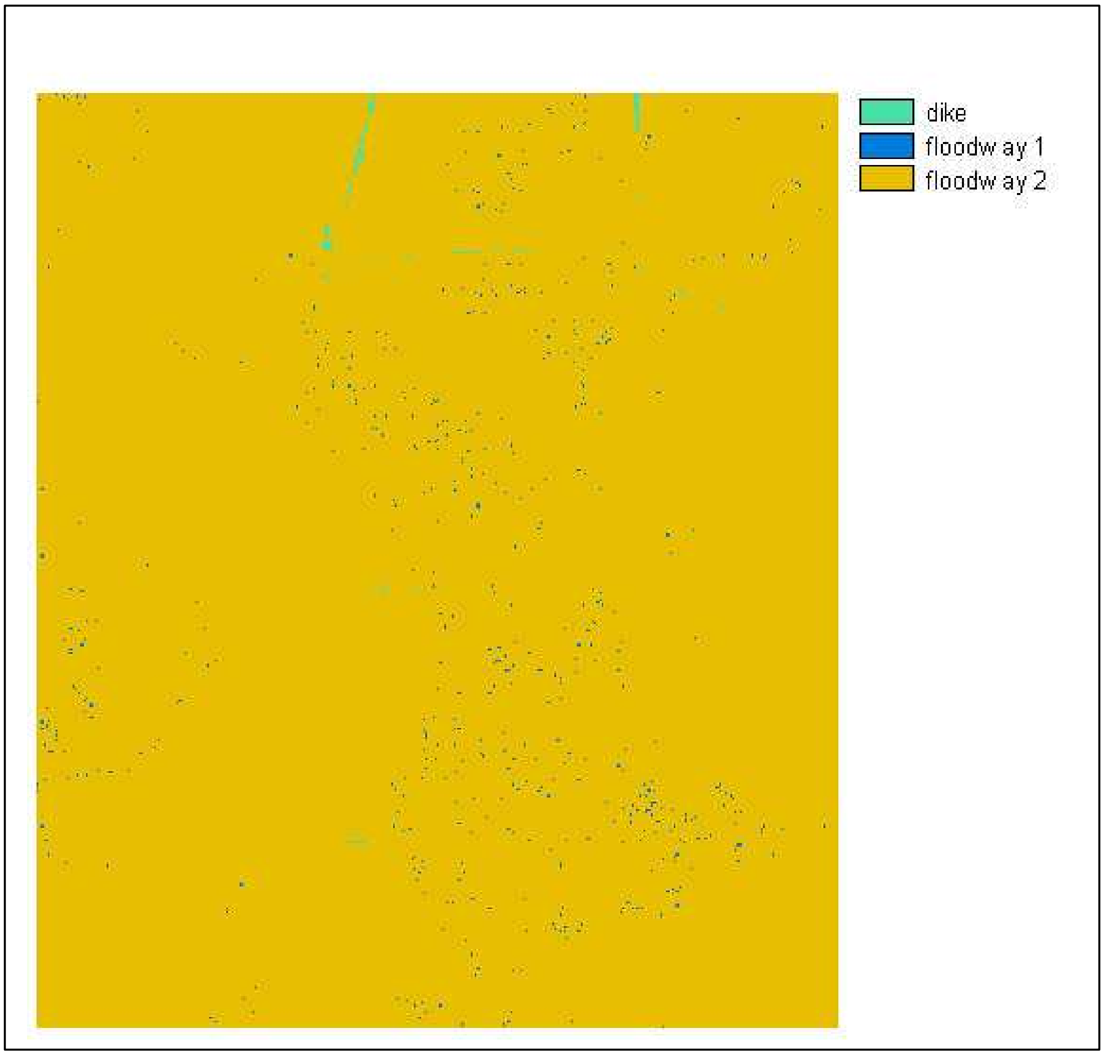

Figure 40: Spatially distributed ranking of three alternatives for weight set #1 using SFCP (Z-MF) approach.

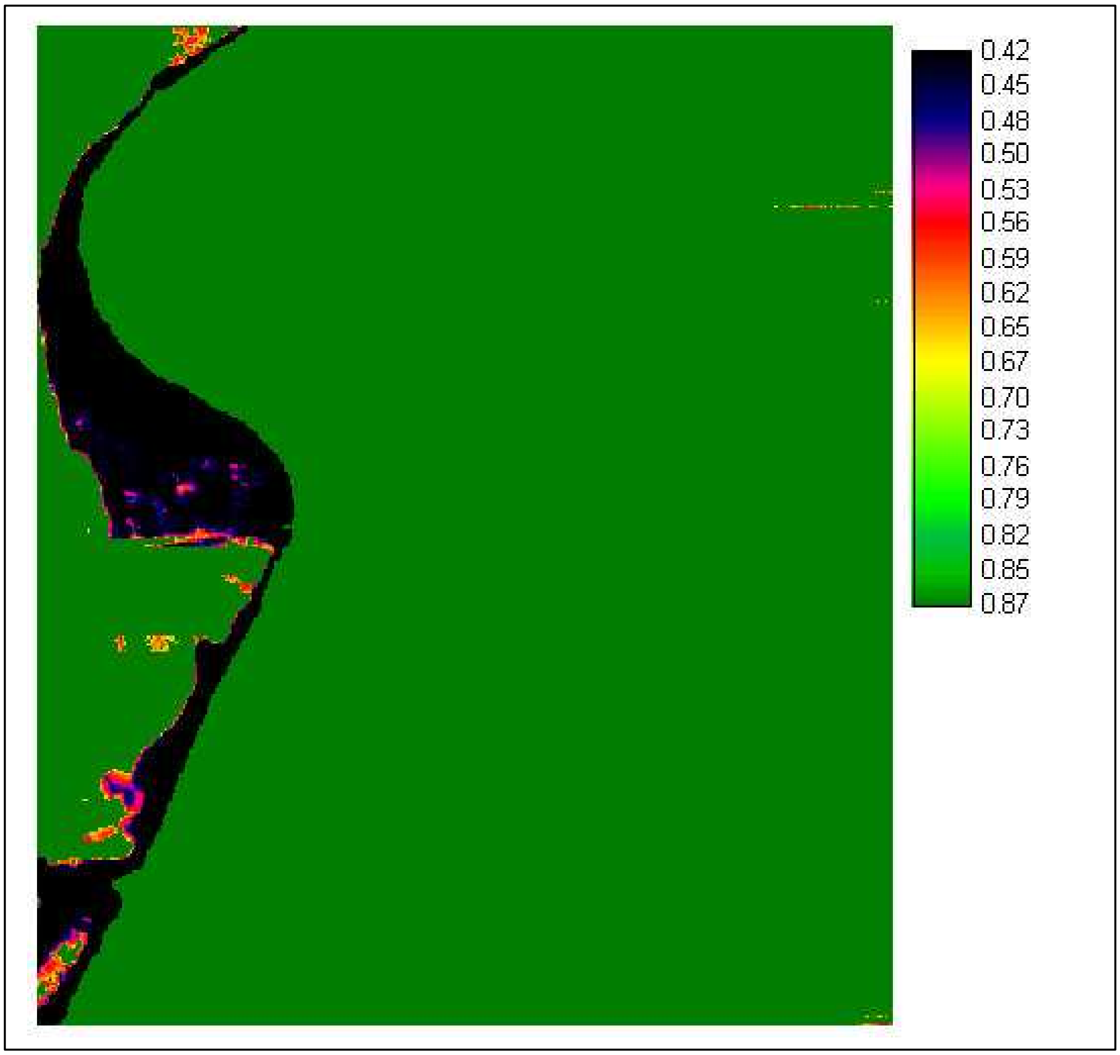

Figure 41: Distance metric image for alternative ‘Dike’ using SFCP (Z-MF) approach for weight set # 2.

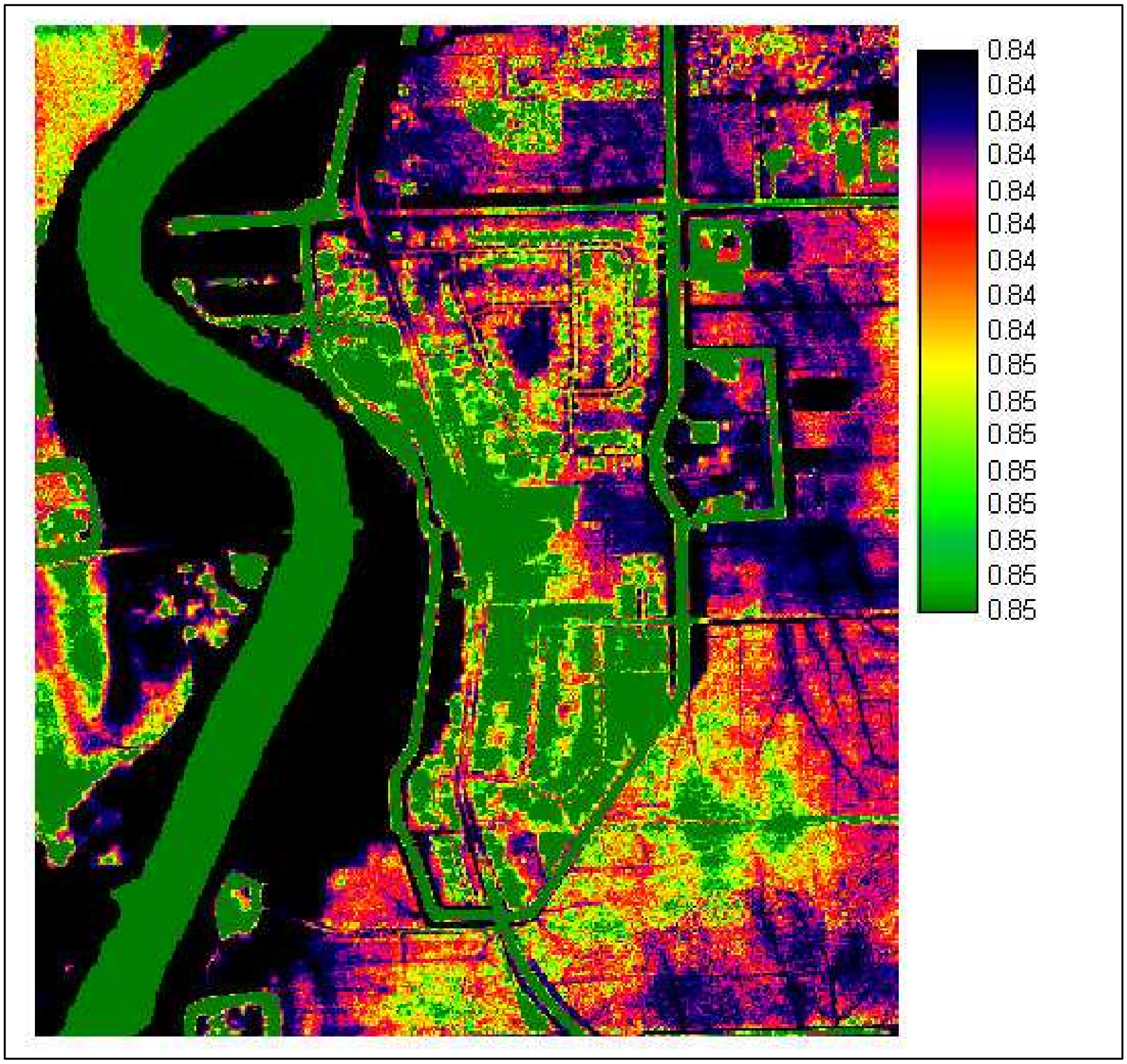

Figure 42: Distance metric image for alternative 'Floodway 1' using SFCP (Z-MF) approach for weight set # 2.

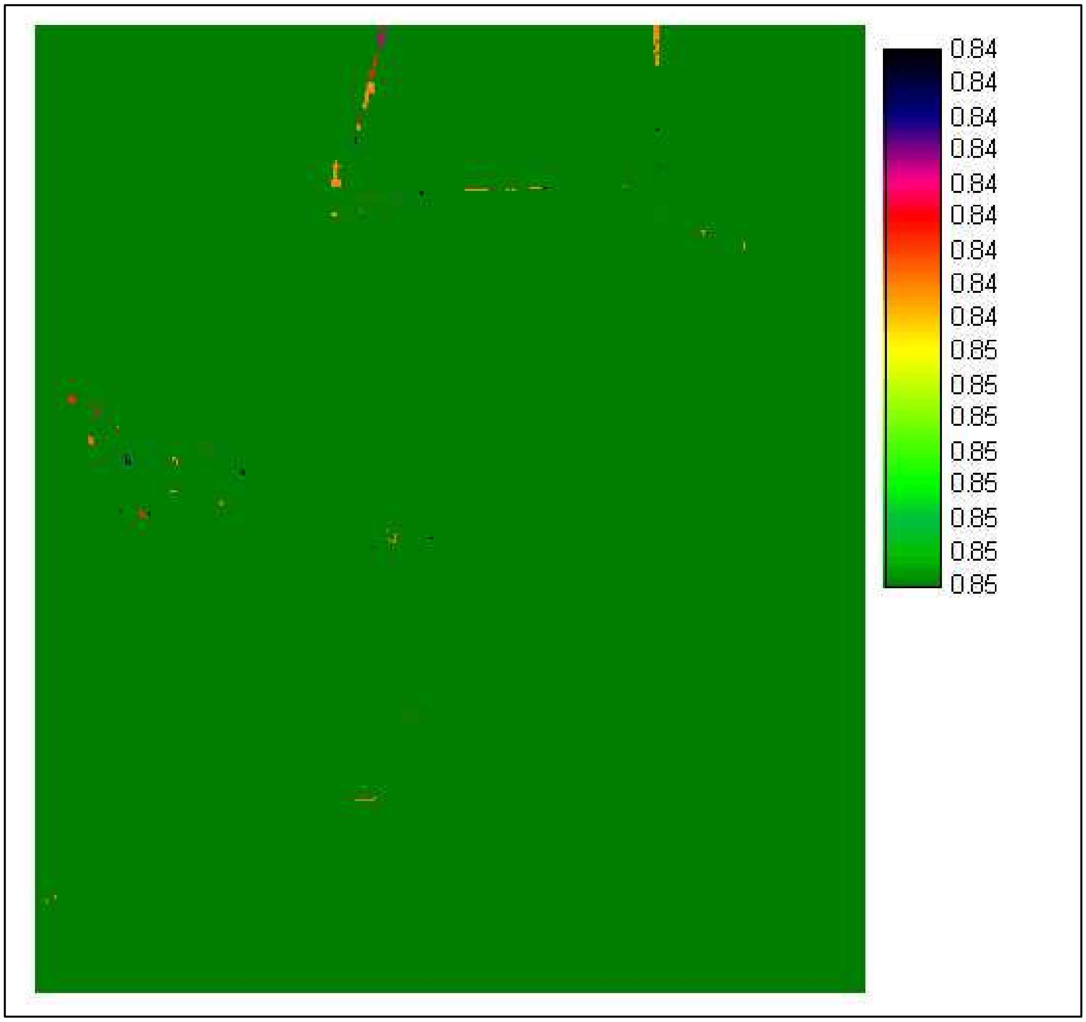

Figure 43: Distance metric image for alternative ‘Floodway 2’ using SFCP (Z-MF) approach for weight set # 2.

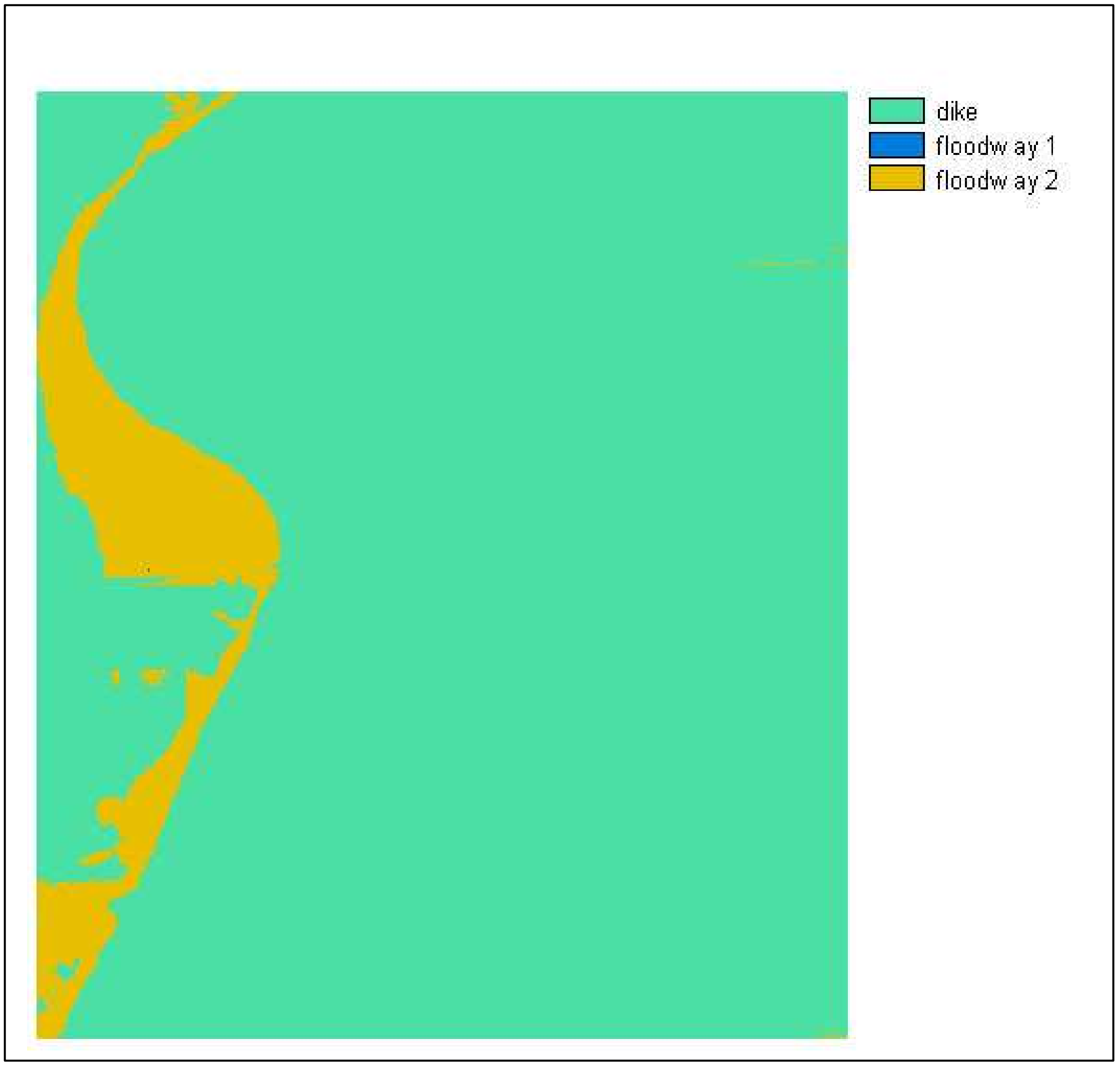

Figure 44: Spatially distributed ranking of three alternatives for weight set # 2 using SFCP (Z-MF) approach.

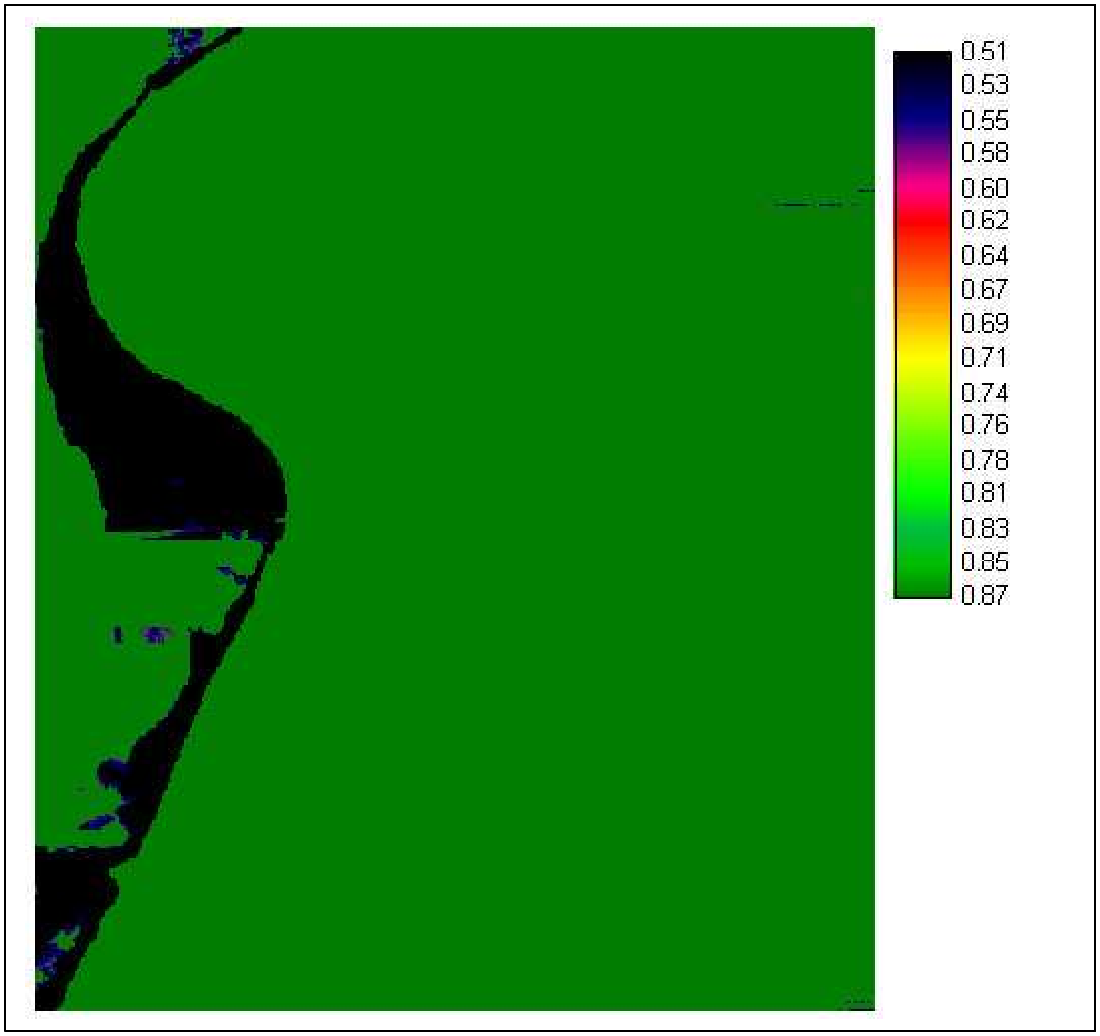

Figure 45: Distance metric image for alternative 'Dike' using SFCP (Z-MF) approach for weight set # 3.

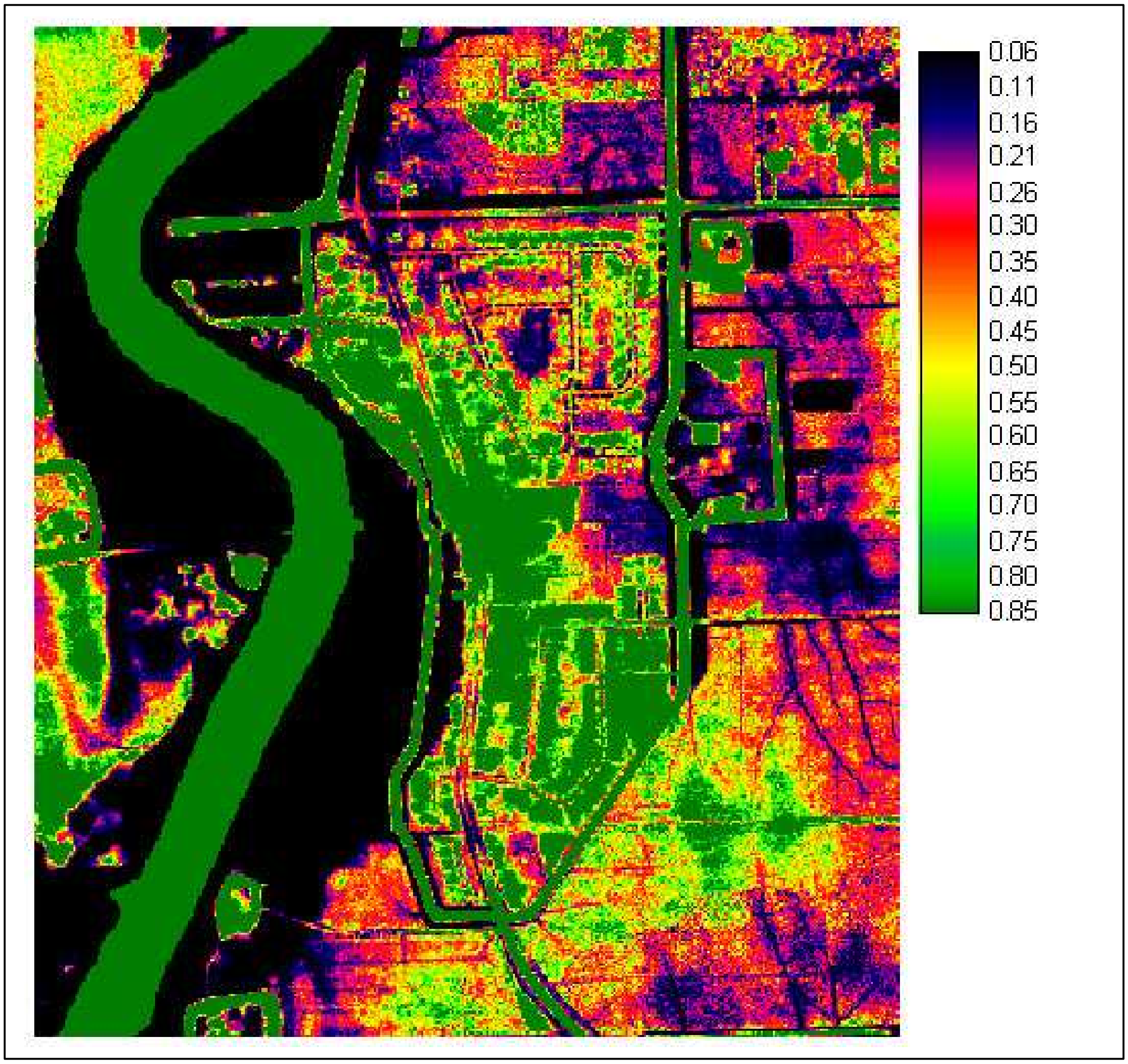

Figure 46: Distance metric image for alternative 'Floodway 1' using SFCP (Z-MF) approach for weight set # 3.

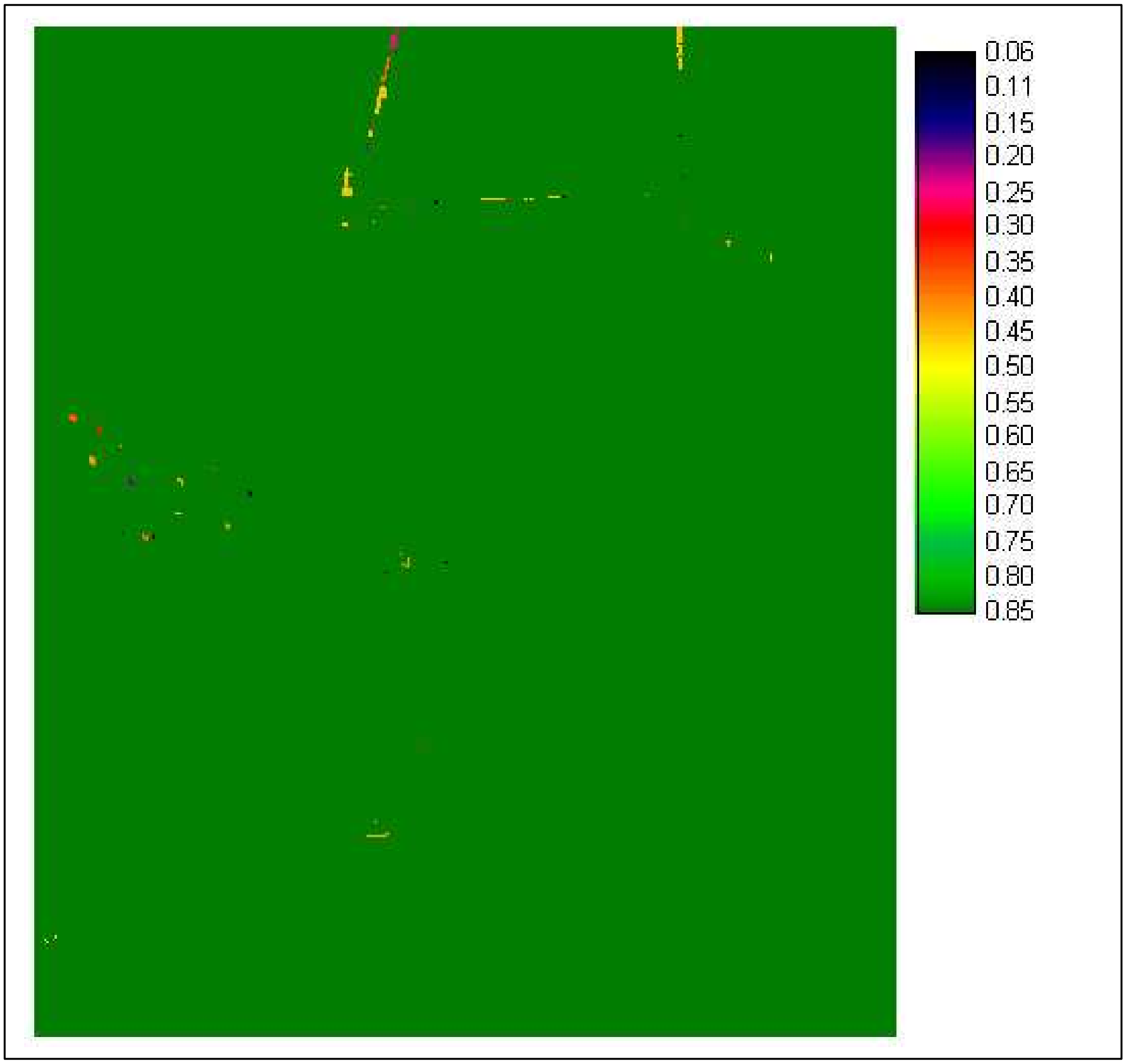

Figure 47: Distance metric image for alternative ‘Floodway 2’ using SFCP (Z-MF) approach for weight set # 3.

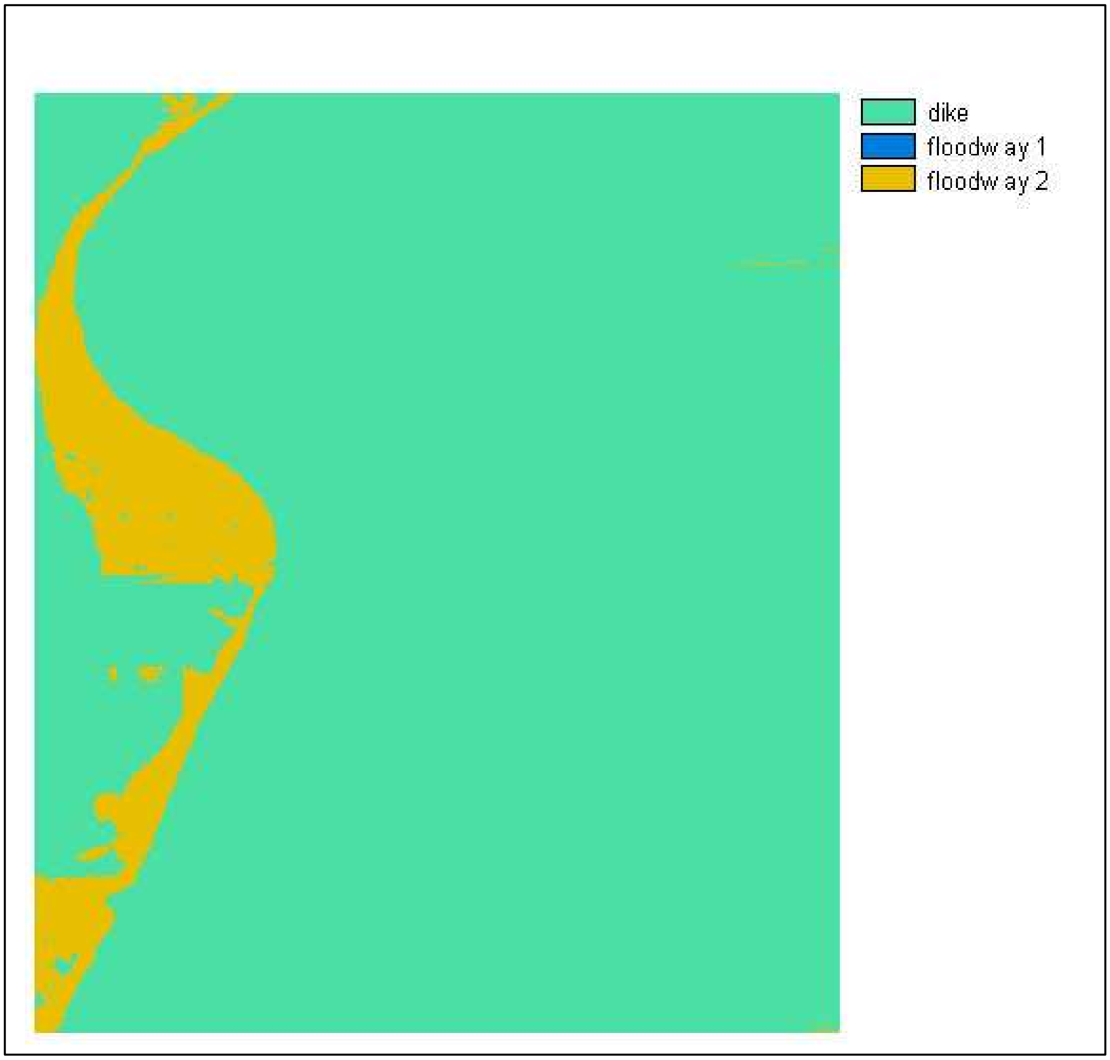

Figure 48: Spatially distributed ranking of three alternatives for weight set # 3 using SFCP (Z-MF) approach.

3.7 Discussion of Results

Using the results illustrated in Section 3.2 for (i) Spatial Compromise Programming (SCP) approach, (ii) Spatial Fuzzy Compromise Programming (SFCP) approach using triangular membership function (T-MF), and (iii) SFCP approach using Z-shaped membership function (Z-MF), the following comparisons are possible:

(a) Comparison of SCP, SFCP using T-MF, and SFCP using Z-MF for the same set of weights;
(b) Comparison of SFCP using T-MF for three different weight sets (Table 2); and
(c) Comparison of SFCP using Z-MF for three different weight sets (Table 2).

3.7.1 Comparison of SCP, SFCP using T-MF, and SFCP using Z-MF for the same set of weights

Looking at all the three approaches, namely SCP, SFCP using T-MF, and SFCP using Z-MF, for weight set # 1 (equal weights assigned to both criteria), it is observed in Figures 10 to 13, Figures 24 to 27 and Figures 36 to 39 that the maximum value of distance metric in case of SCP analysis is much lower than SFCP analysis using T-MF and Z-MF. This observation can lead to an inference that SFCP analysis is better than SCP analysis as according to Equation (12) larger the distance metric value higher the degree of membership. Alternative 'Dike' distance metric images (Figures 10, 24 and 36) indicate a drastic difference between SFCP approach using Z-MF and the other two approaches. In SFCP using Z-MF distance metric image (Figure 36), a clear demarcation is shown between absolutely unprotected region (very dark) and rest of the region without any variation in degree of protection by the alternative 'Dike'. Figures 11, 25 and 37 suggest that using SCP approach some of the buildings are not protected, whereas, SFCP approach using T-MF shows the same cluster of buildings being protected. SFCP approach using Z-MF distance metric captures the spatial variability of protection very well by clearly indicating the area adjacent to the Red River (floodplain) as unprotected area, while, the rest of the region can be seen visibly divided into various degrees of protection. Similarly, for alternative ‘Floodway 2’, the distance metric images (Figures 12, 26 and 38) suggest that some of the buildings that are shown as unprotected in SCP analysis are actually shown as fairly well protected in SFCP analysis using T-MF while picture shown by SFCP analysis using Z-MF is entirely different. The difference between the ranges of distance metric values also should be noted.

Looking at the final ranking of alternatives, SCP approach (Figure 13) suggests that alternative ‘Dike’ (shown in green) provides the highest protection for most of the region except for the left bank of the Red River where alternative ‘Floodway 2’ (shown in yellow) is found to be providing better protection and some scattered spots where alternative ‘Floodway 1’ (shown in blue) offers better protection. SFCP approach using T-MF (Figure 27) illustrates that alternative ‘Floodway 1’ provides the highest protection for most of the study region and alternative ‘Floodway 2’ offers protection to some buildings, roads and the floodplains on both sides of the river. SFCP approach using Z-MF indicates that alternative ‘Floodway 2’ is the best compromise for most of the region and alternative ‘Floodway 1’ is recommended for some scattered locations. Point to note, here, is that alternative ‘Dike’ dominates the SCP analysis, alternative ‘Floodway 1’ provides better protection to most of the region in SFCP analysis using T-MF and ‘Floodway 2’ dominates the entire region using SFCP analyses using Z-MF. Separate comparison of all the alternatives using three different approaches gives an impression that selection of one approach over the other is not possible at this point where comparison of alternatives has been done based on equal weight assignment to both the criteria.

Weight set # 2 (Table 2) assigns different weights to two different criteria considered in this study. Figures 14 – 17 illustrate SCP approach for weight set # 2, Figures 28 – 31 show SFCP approach using T-MF and Figures 40 – 43 present SFCP approach using Z-MF. Comparing the results for different approaches it can be noticed that individual images of distance metric of alternative ‘Dike’ for SCP and SFCP using T-MF are not very different. However, SFCP using Z-MF provides quite a different picture in terms of varying degree of protection offered by alternative 'Dike'. Alternative 'Floodway 1' distance metric images can be seen in Figures 15, 29 and 41. SCP approach in Figure 15 illustrates that 'Floodway 1' does not provide a high level of protection for most of the buildings in the region, while it is found to be effective for roads and very effective for rest of the study region. SFCP using T-MF in Figure 29 shows a varying degree of effectiveness for 'Floodway 1' in the region with most of the area being well protected with this alternative with lesser protection of the buildings and medium protection of the roads. SFCP using Z-MF in Figure 41 demonstrates that 'Floodway 1' does not provide any protection for the floodplain. Suitability of this alternative varies significantly in the rest of the study region. Finally, a look at Figures 16, 30 and 42 explains the degree of suitability of alternative 'Floodway 2' using SCP, SFCP using T-MF and SFCP using Z-MF. All the three approaches portray a different picture of suitability for this alternative.

Finally, Figures 17, 31 and 43 present the ranking of alternatives using the three approaches. SCP and SFCP using Z-MF seem in agreement in most of the study region except for some scattered spots that are shown as suitable for alternative 'Floodway 2' in Figure 17 (SCP). SFCP using T-MF (Figure 31), however, illustrates a completely different picture of suitability of the three alternatives. In this case, alternative 'Floodway 1' is found to be suitable in most of the region and 'Floodway 2' is found to be suitable in the floodplains on both sides of the river plus some buildings and roads. Alternative 'Floodway 2' is mostly found suitable only in floodplain on the left side of the river using SCP and SFCP using Z-MF analyses.

Lastly, weight set # 3 (Table 2), which also assigns different weights to both criteria, produced distance metric images shown in Figures 18 – 20 (SCP approach), Figures 32 – 34 (SFCP using T-MF) and Figures 44 – 46 (SFCP using Z-MF). Figures 18 is different from Figures 34 and 44 in every way. Figure 44 illustrates unsuitability of 'Dike' for the protection of floodplain on the left bank of Red River and suitability for the rest of the region. This is due to the fact that the dike has been simulated only on the right bank of the river to protect the community of St. Adolphe. Similarly, alternative 'Floodway 1' is found to be suitable in almost same region (with little variation in degree of suitability) using SCP (Figure 19) and SFCP using T-MF (Figure 33) approaches. SFCP using Z-MF approach presents a different scenario in terms of categorizing the region according to suitability for alternative 'Floodway 1' (Figure 45). Alternative 'Floodway 2' distance metric images (Figures 20, 34 and 46) are not very different from each other for all the three approaches except for SFCP using Z-MF in which different scattered points are shown as less suitable for this alternative.

Ranking of the three alternatives using three approaches are illustrated in Figures 21, 35 and 47. As demonstrated by these figures, it can be noted that all the three approaches portray a different scenario in terms of choice of alternatives for flood protection in the study region. SCP analysis shows alternative 'Floodway 2' as most protective, alternative 'Floodway 1' is next and alternative 'Dike' is shown to protect only some scattered portions. SFCP using T-MF analysis chooses alternative 'Dike' for most of the region and 'Floodway 2' for left river bank floodplain with some portions suitable for alternative 'Floodway 1'. SFCP using Z-MF shows a completely different scenario by choosing alternative 'Dike' and 'Floodway 2' as suitable alternatives.

3.7.2 Comparison of SFCP using T-MF for three different weight sets

Comparison of the results obtained for three different weight sets (Table 2) with SFCP using T-MF approach can be done through the distance metric images (Figures 24 – 26) obtained by assigning equal weights to both the criteria (flood depth and damage) and their ranking image shown in Figure 27. As it is clear from Figure 27 alternative 'Floodway 2' has been chosen to be suitable for the floodplains and some of the roads and buildings. For the rest of the region alternative 'Floodway 1' is found to be suitable. Weight set # 2 in which less importance has been given to criterion 'flood depth' produced distance metric images given in Figures 28 – 30. As expected, these distance metric images are quite different than those for the weight set # 1. Due to higher importance to given to damage, certain buildings and roads have come up prominent in case of 'Floodway 1' and 'Floodway 2' alternatives. Alternative 'Dike' protects the whole of community of St. Adolphe therefore, most of the region falls under the high degree of membership. Ranking of the alternatives using weight set # 2 (Figure 31) illustrates that alternative 'Floodway 2' is suitable for protection of some buildings and floodplains (little less compared to weight set # 1 ranking). Weight set # 3, in which less importance has been given to damage and more importance to flood depth, buildings and roads have not come out as prominent features (Figures 32 – 34). Floodplain on the left riverbank in case of alternative 'Dike' and floodplain on both riverbanks in case of alternative 'Floodway 1' are more prominently shown. Ranking of alternatives for this weight set also portrays a different scenario with 'Floodway 2' being more effective for the left bank floodplain and 'Floodway 1' for some portions while 'Dike' protects most of the area including the right bank floodplain.

3.7.3 Comparison of SFCP using Z-MF for three different weight sets

SFCP using Z-MF approach distance metric results for alternative 'Dike' are shown in Figures 36, 40 and 44. Obviously, assigning of weights should play an important role in arriving at the preferred suitability of a particular alternative in the entire region. However, with less weight to 'flood depth' and more weight to 'damage' vs. more weight to 'flood depth' and less weight to 'damage' the difference between the distance metric images is not much. Similarly, alternative 'Floodway 1' distance metric images (Figures 37, 41 and 45) demonstrate a very little preference to regions according to importance assigned to each of the two criteria. Ranking of the three alternatives in case of each of the three weight sets (Figures 39, 43 and 47) illustrates the choice of 'Dike' and 'Floodway 2' for most of the region for weight set # 2 and weight set # 3. However, with equal weight assigned to both the criteria, SFCP using Z-MF shows a different choice of alternatives. 'Floodway 2' is found to be suitable in most of the area in this case, 'Floodway 1' and 'Dike' are found to be flood protective in scattered portions.

If only the ranked alternatives' produced by both SFCP using T-MF and SFCP using Z-MF were to be compared, it is apparent that SFCP using T-MF makes more sense because there is difference between ranking of alternatives using SFCP (T-MF) for weight set # 2 (Figure 31) and weight set # 3 (Figure 33). On the other hand the ranking of alternatives using SFCP (Z-MF) for weight set # 2 (Figure 43) and weight set # 3 (Figure 47) does not show a significant effect of differently assigned weights.

4. CONCLUSIONS

Existing multi objective analysis techniques have certain limitations in terms of their ability to address certain issues related to problems, which are spatial in nature and are susceptible to uncertainties and vagueness associated with natural processes that are being represented. Uncertainties could also arise from the data monitoring equipment and/or from lack of knowledge. For instance, uncertainties are involved in criteria values and parameter values associated with flood management process when various flood protection alternatives are to be judged and chosen for implementation. Often there is a possibility that different flood protection alternatives provide best protection for different locations in the region of interest. Therefore, to incorporate spatial variability factor and capability to address uncertainties, an integration of Spatial Compromise Programming (SCP), which facilitates spatial variability and Fuzzy Compromise Programming (FCP), which provides means to account for uncertainties has successfully been attempted in this work. The proposed multi objective analysis technique, named as Spatial Fuzzy Compromise Programming (SFCP) has been discussed in detail and applied to a case study of flood management for Red River Basin near community of St. Adolphe. Like SCP and FCP, SFCP is based on the concept of Compromise Programming (CP) method with inclusion of fuzzy theory for addressing the uncertainties and GIS for spatial factor.

In the present work various flood protection alternatives are being evaluated and ranked spatially in the region of interest for flood management purpose. With implementation of SFCP, it has been illustrated that decision making can be improved considerably in terms of accuracy and efficiency by accounting for spatial variability and uncertainty factors together. Fuzzification of the criteria values, parameter value and the weights assigned to each of the criteria value is being achieved using triangular membership function (T-MF) and Z-shaped membership function (Z-MF) to account for uncertainties associated with criteria values, weights and the parameters. Use of GIS technology has made it possible to produce maps (images) of damaged property (buildings, roads and agriculture) and flood depth for evaluation of various potential flood protection alternatives. Appropriate fuzzy membership function (to account for vagueness associated with criteria values) can be chosen based on the nature of the problem. Not necessarily all the inputs to the distance metric equation need to be fuzzified. Some inputs can be crisp depending on the reliability of their values. Different membership functions can be assigned to criteria values; their weights; and parameters by the decision maker thus increasing the flexibility. From decision and representation point of view as well SFCP performs better compared to other methods because the choices are clearly laid out in front of the decision maker. It is possible to assess various alternatives based on many other objectives as well. Applicability of this method does not restrict the user to only flood protection measures assessment. It can be used in any other complex decision making process which needs to be carried out spatially and has some vagueness involved within that needs to be addressed.

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APPENDIX A – Basic Fuzzy Mathematics

Definition 1. (Classical set)

Classical, or a crisp set, is one which assigns grades of membership of *either 0* or *1* to objects within their universe of discourse. To say it in another way, objects either belong to or do not belong to a certain class; or object either posses a certain property, or they do not; there is no middle ground. The type of a function that describes this is called a characteristic function.

Definition 2. (Fuzzy set)

A fuzzy set is one which assigns grades of membership *between 0* and *1* to objects within its universe of discourse. If X is a universal set whose elements are $\{x\}$, then, a fuzzy set A is defined by, its membership function,

$$\mu_A : X \rightarrow [0,1] , \qquad \text{(A1)}$$

which assigns to every x a degree of membership μ_A in the interval $[0,1]$.

A fuzzy set can be represented by a continuous membership function $\mu_A(x)$, or by a set of discrete points. The latter is denoted by ordered pairs,

$$A = \{(x, \mu_A(x))\}, \quad x \in X . \qquad \text{(A2)}$$

It is worth noting that a fuzzy set, whose degree of membership is only *0* and *1*, reduces to a crisp set.

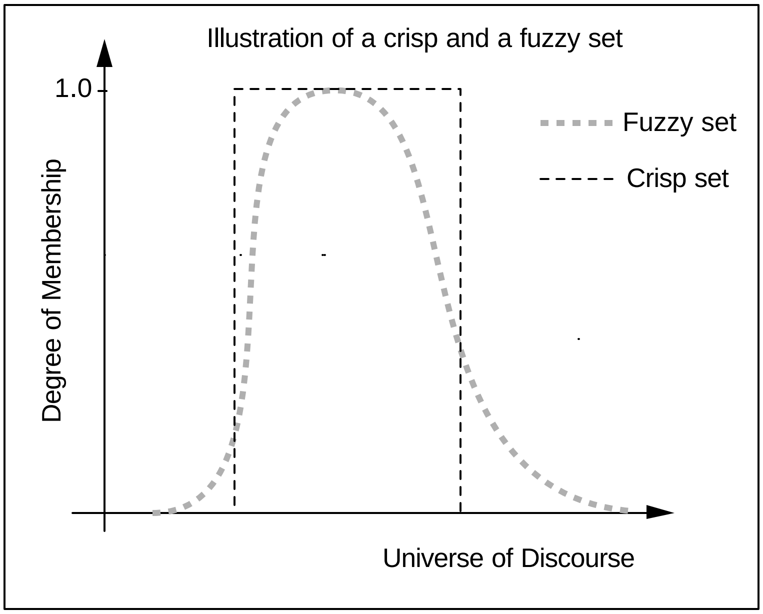


Figure A1. Illustration of a crisp and a fuzzy set

Definition 3. (Support of a fuzzy set)

Support of a fuzzy set *A* (written as *supp(A)*) is a (crisp) set of points in *X* for which μ_A is positive. An alternate way of saying this would be that the support of a fuzzy set *A* is the valid universe of discourse of *A* (i.e., all valid *x's*). Mathematically stated,

$$supp(A) = \{x \in X \mid \mu_A(x) > 0\}. \tag{A3}$$

Synonyms of support are degree of fuzziness or a fuzzy spread.

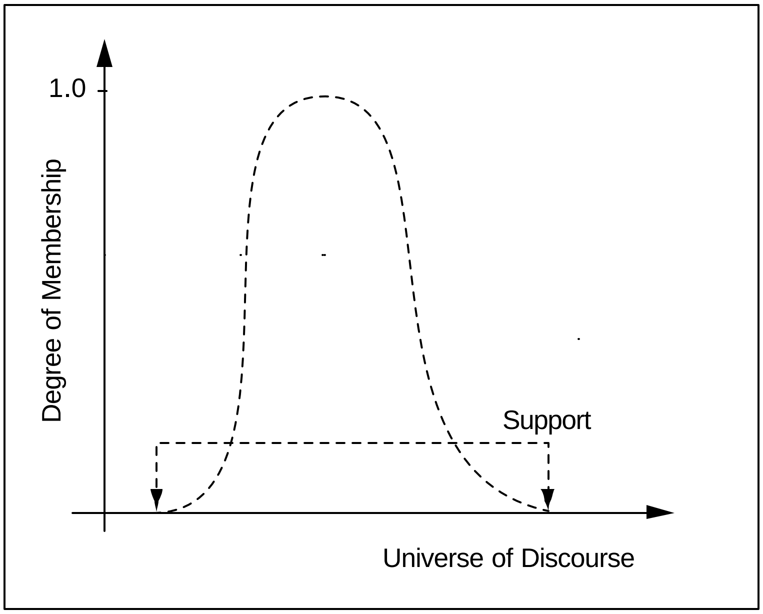


Figure A2. Support of a fuzzy set

Definition 4. (Normal fuzzy set)

A fuzzy set *A* is normal if its maximal degree of membership is unity (i.e., there must exist at least one *x* for which $\mu_A(x) = 1$). Of course, non-normal fuzzy sets have maximum degree of membership less than one.

Definition 5. (Convex fuzzy set)

A fuzzy set *A* is convex if and only if it satisfies the following property:

$$\mu_A(\lambda x_1 + (1-\lambda)x_2) \geq min(\mu_A(x_1), \mu_A(x_2)) \quad \text{(A4)}$$

where λ is in the interval $[0,1]$, and $x_1 < x_2$. An example of a convex, as well as a non-convex fuzzy set is illustrated in Figure A3.

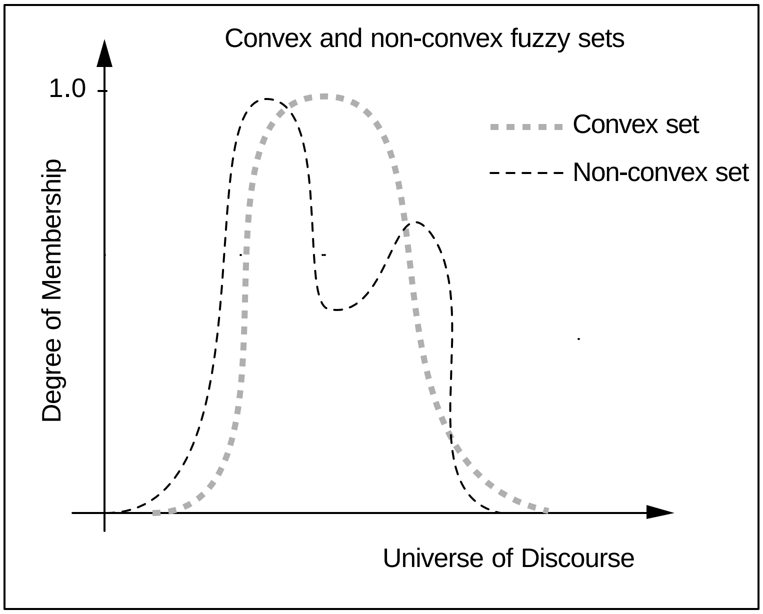


Figure A3. Convex and non-convex fuzzy sets

Remark: All fuzzy sets encountered in this report are both normal and convex.

Definition 6. (Intersection and union of fuzzy sets)

Intersection of fuzzy set A with fuzzy set B is:

$$\mu_{A \cap B}(x) = min(\mu_A(x), \mu_B(x)) \tag{A5}$$

Union if two fuzzy sets is similarly defined:

$$\mu_{A \cup B}(x) = max(\mu_A(x), \mu_B(x)) \tag{A6}$$

Note that intersection of two fuzzy sets is the largest fuzzy sets contained within A and B, and union is the smallest. See Figure A4 for clarification.

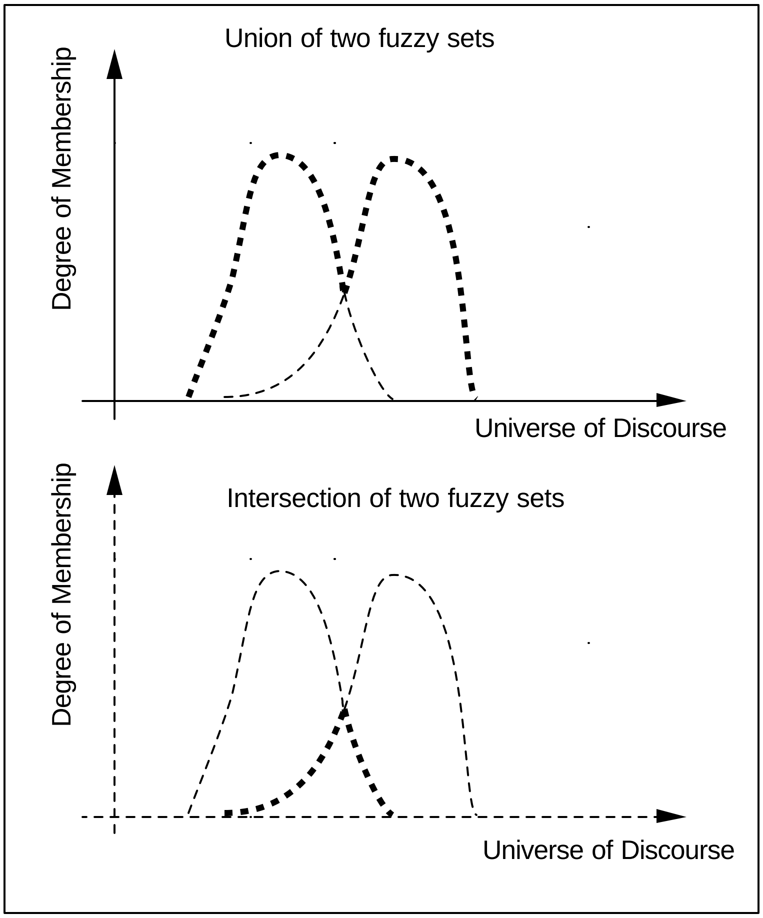


Figure A4. Union and intersection of two fuzzy sets

Definition 7. (Supremum and infimum of fuzzy sets)

Supremum, denoted by *sup*, is the largest possible value within given set, while infimum, denoted by *inf*, is the smallest value in a given set.

Definition 8. (λ-cut of a fuzzy set)

λ-cut of a fuzzy set is defined as crisp set A^{α} (or a crisp interval) for a particular degree of membership, α. Mathematically stated,

$$A^{\alpha} = [\, a^{\alpha}, b^{\alpha} \,] \tag{A7}$$

where α, as before, can take on values between $[0,1]$.

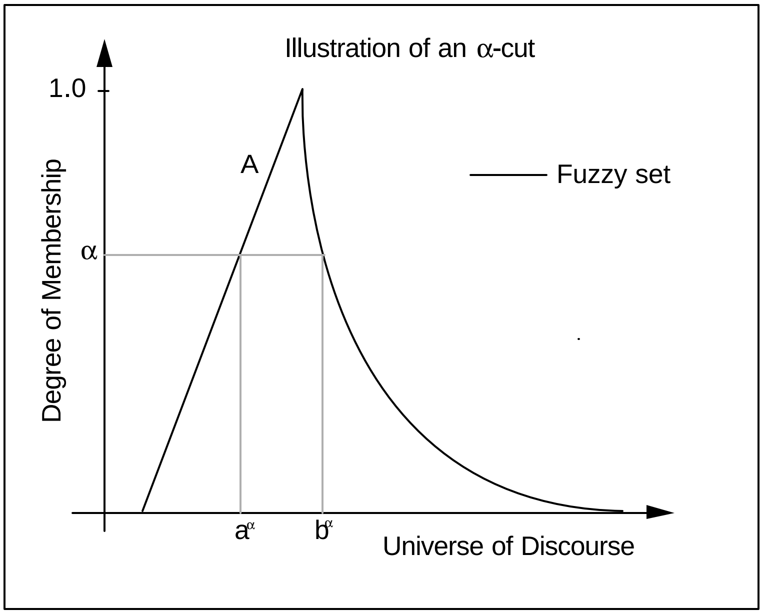


Figure A5. Illustration of an α-cut

Definition 9. (Fuzzy numbers)

A fuzzy number is a fuzzy set which is both normal and convex. In addition, the membership function of a fuzzy number must be piecewise continuous.

Most common types of fuzzy numbers are triangular and trapezoidal. Other types of fuzzy numbers are possible, such as bell-shaped or gaussian fuzzy numbers, as well as a variety of one sided fuzzy numbers. These will not be covered here. The interested reader is referred to a book by Klir and Yuan (1995) for more information on other types of fuzzy numbers. Triangular fuzzy numbers are defined by three parameters, while trapezoidal require four parameters.

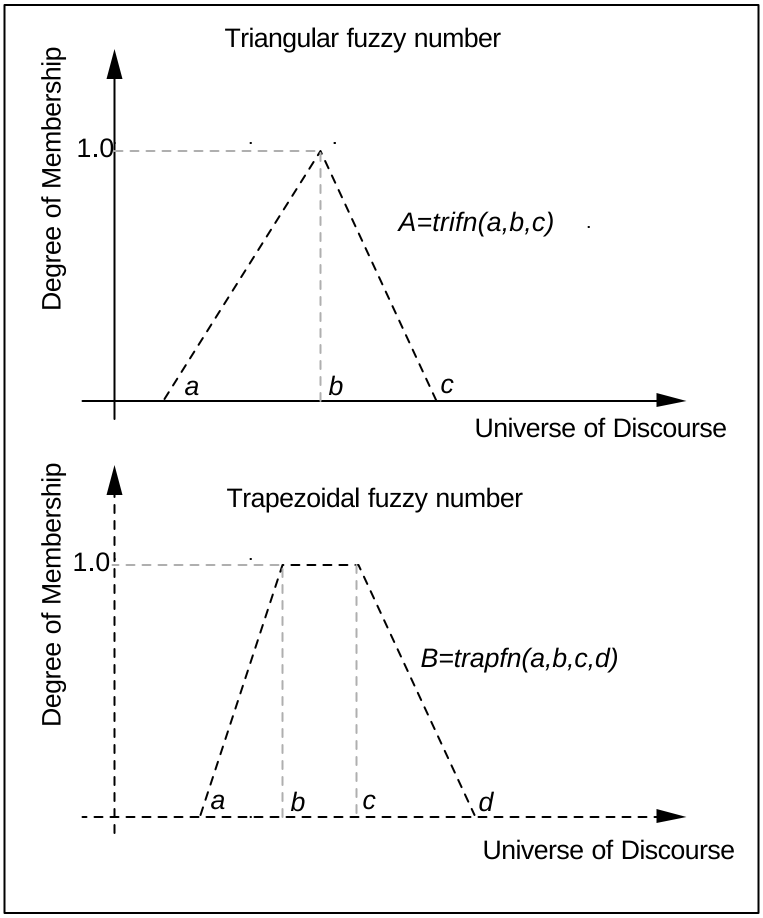


Figure A6. Triangular and trapezoidal fuzzy numbers

Fuzzy Arithmetic

A popular way to carry out fuzzy arithmetic operations is by way of interval arithmetic. This is possible because any α -cut of a fuzzy number is always an interval (see definition 8). Therefore, any fuzzy number may be represented as a series of intervals (one interval for every α-cut). In the Matlab code that was produced, 101 α -cuts (or intervals) were made, which means that α -cuts were made for $\alpha = 0, 0.01, 0.02, 0.03, \ldots , 0.98, 0.99, 1.0$. Now, this means that there exist *101* intervals on which we are to perform interval arithmetic operations.

The basics of interval arithmetic are given next. For any two intervals, $[a, b]$ and $[d, e]$, the arithmetic operations are performed in the following way:

Addition: $[a, b] + [d, e] = [a+d, b+e];$ (A8)

Subtraction: $[a, b] - [d, e] = [a-e, b-d];$ (A9)

Multiplication: $[a, b] \cdot [d, e] = [min(ad, ae, bd, be), max(ad, ae, bd, be)];$ (A10)

Power: $[a, b]^{[d,e]} = [min(a^d, a^e, b^d, b^e), max(a^d, a^e, b^d, b^e)];$ (A11)

Division: $[a,b] / [d, e] = [min(a/d, a/e, b/d, b/e), max(a/d, a/e, b/d, b/e)],$ (A12)

provided that $0 \notin [d, e]$.

Since any fuzzy number can be represented by a series of crisp intervals, we can then apply interval arithmetic operations (such as addition, subtraction, multiplication, division, power) and obtain an alternate way of performing fuzzy arithmetic. This is what most texts (and Matlab) consider as fuzzy arithmetic. In addition, this technique is *more* computationally efficient than brute force/dynamic search combination, but its downfall is that it cannot handle multi-modal fuzzy sets (i.e. multi-modal fuzzy sets cannot be expressed as intervals). An excellent text on fuzzy arithmetic is one by Kaufman and Gupta (1985); also, Klir and Yuan (1995) in their book cover the basics of fuzzy arithmetic rather well.

Note: Bender and Simonovic (1996) developed a different method of performing fuzzy arithmetic. Their method is based on brute force complimented with dynamic searches, which are used to lower computation time. An advantage of their method is that it's able to perform fuzzy arithmetic on all types of fuzzy sets, not just fuzzy numbers. However, even with dynamic searches, the method is *extremely* computationally intense.

Therefore, it can be concluded that if fuzzy arithmetic is required for non-convex (or multi-modal) fuzzy sets, brute force/dynamic search method should be used. If on the other hand, fuzzy arithmetic is required to be performed on fuzzy numbers, then application of interval arithmetic is sufficient.

APPENDIX B – Hydraulic Modeling using HEC-RAS

US Army Corps of Engineers' River System Analysis software has following steps to follow in order to carry out steady flow analysis simulation.

1. Draw the schematic of the river system. Figure B1 shows the schematic diagram of Red River floodway (called Morris Floodway).

2. Enter cross section data, which includes River Station (RS) number, its elevation, downstream reach lengths, Manning's n values, Contraction and Expansion coefficients. Figure B2 is an illustration of a cross section for this study.

3. Enter steady flow data. Flow data are entered from upstream to downstream for each reach. Once a flow value is entered at the upstream end of a reach, it is assumed that the flow remains constant until another flow value is encountered within the reach. In this study 1997 Red River flood flow data has been used.

4. Running the simulation gives several output options, such as, cross section plots, rating curves, detailed tabular output at a specific cross section, and limited tabular output at many cross sections, can be seen. Figure B5 is an illustration of cross section output.

5. For the purpose of simulating the three flood alternatives, namely, Dike, Floodway 1, and Floodway 2, modifications in input data files were made in the following way;

    - Dike: Option 'Levees' allows the user to establish a left and/or right levee station and elevation on any cross section. When levees are established, no water can go to the left of the left levee station or to the right of the right levee station until either of the levee elevation is exceeded. Using this option one levee has been established at the right bank of Red River, where St. Adolphe is situated. Simulation is run and water surface elevation in the rest of the area has been obtained for the alternative of 'Dike'. Figure B3 illustrates a cross section data window and Figure B4 shows how a levee data has been entered at St. Adolphe for simulation.

- Floodway 1: Value of total discharge at the existing Red River floodway is altered in such a way that the water surface elevation went up by one meter from its original (1997 Red River flood) level.

- Floodway 2: Value of total discharge at the existing Red River floodway entrance has been altered in such a way that the water surface elevation dropped by one meter from its original (1997 Red River flood) level.

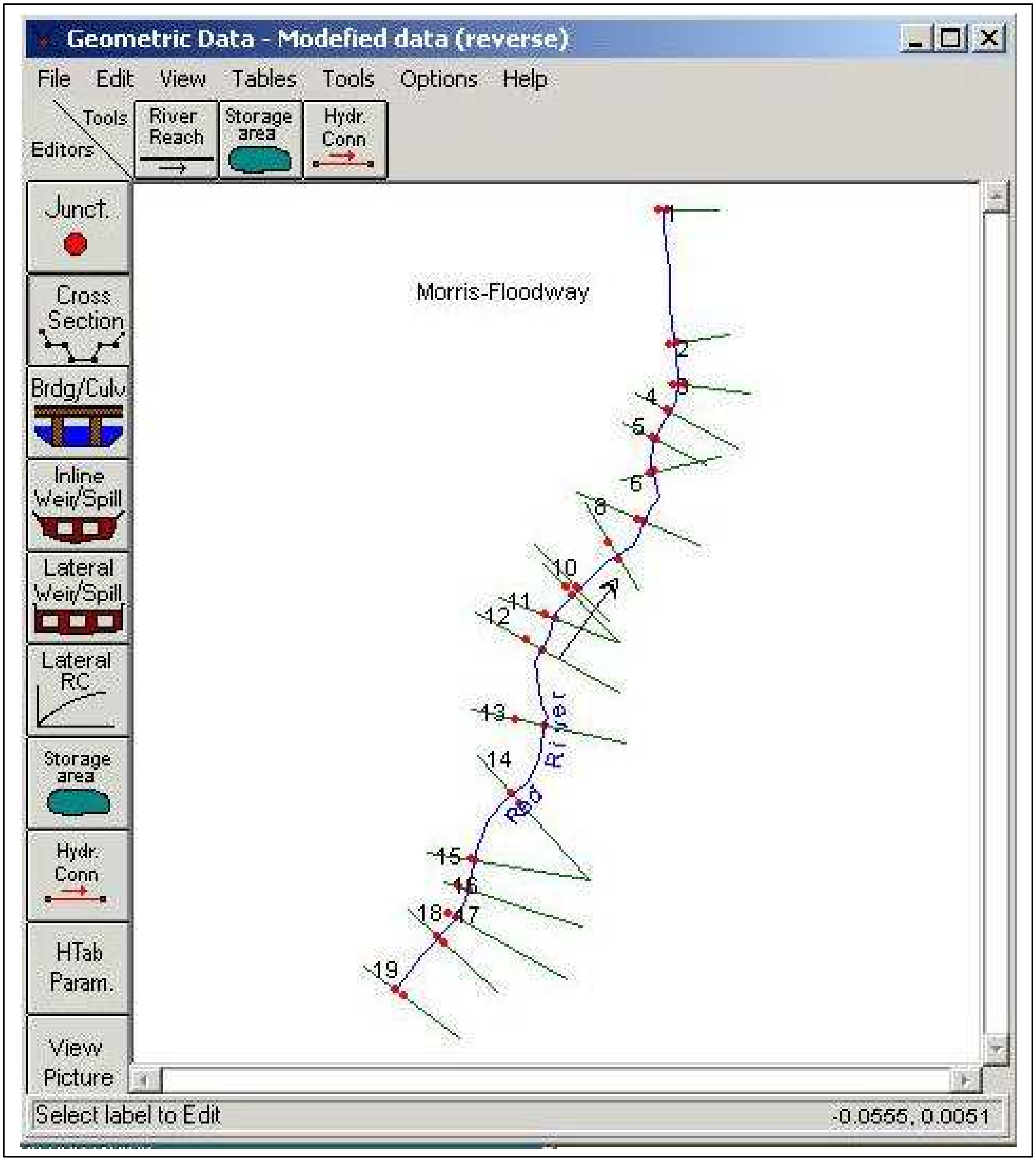


Figure B1: Red River schematic around the floodway river stations.

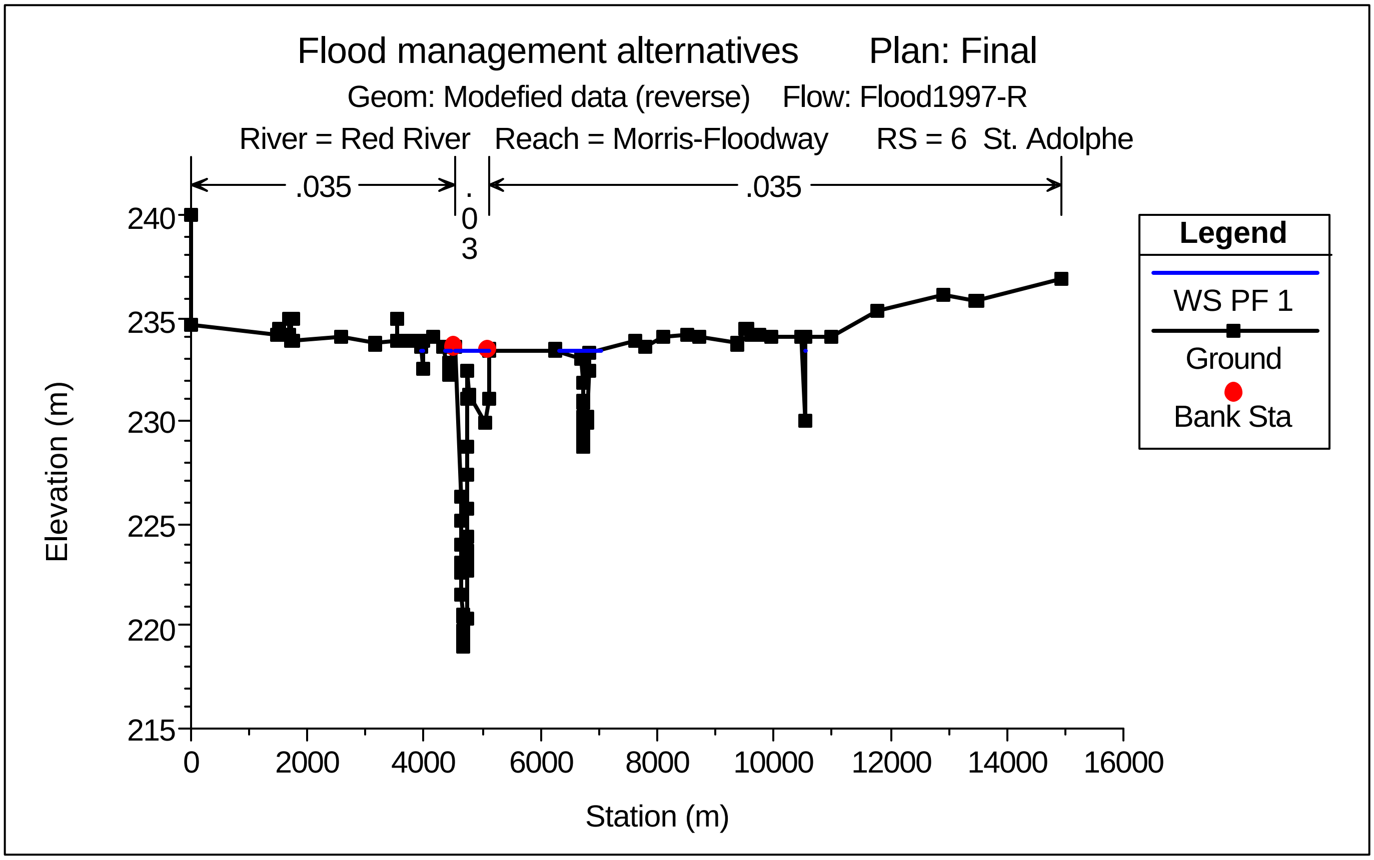


Figure B2: Cross section plot at river station number 6 at St. Adolphe.

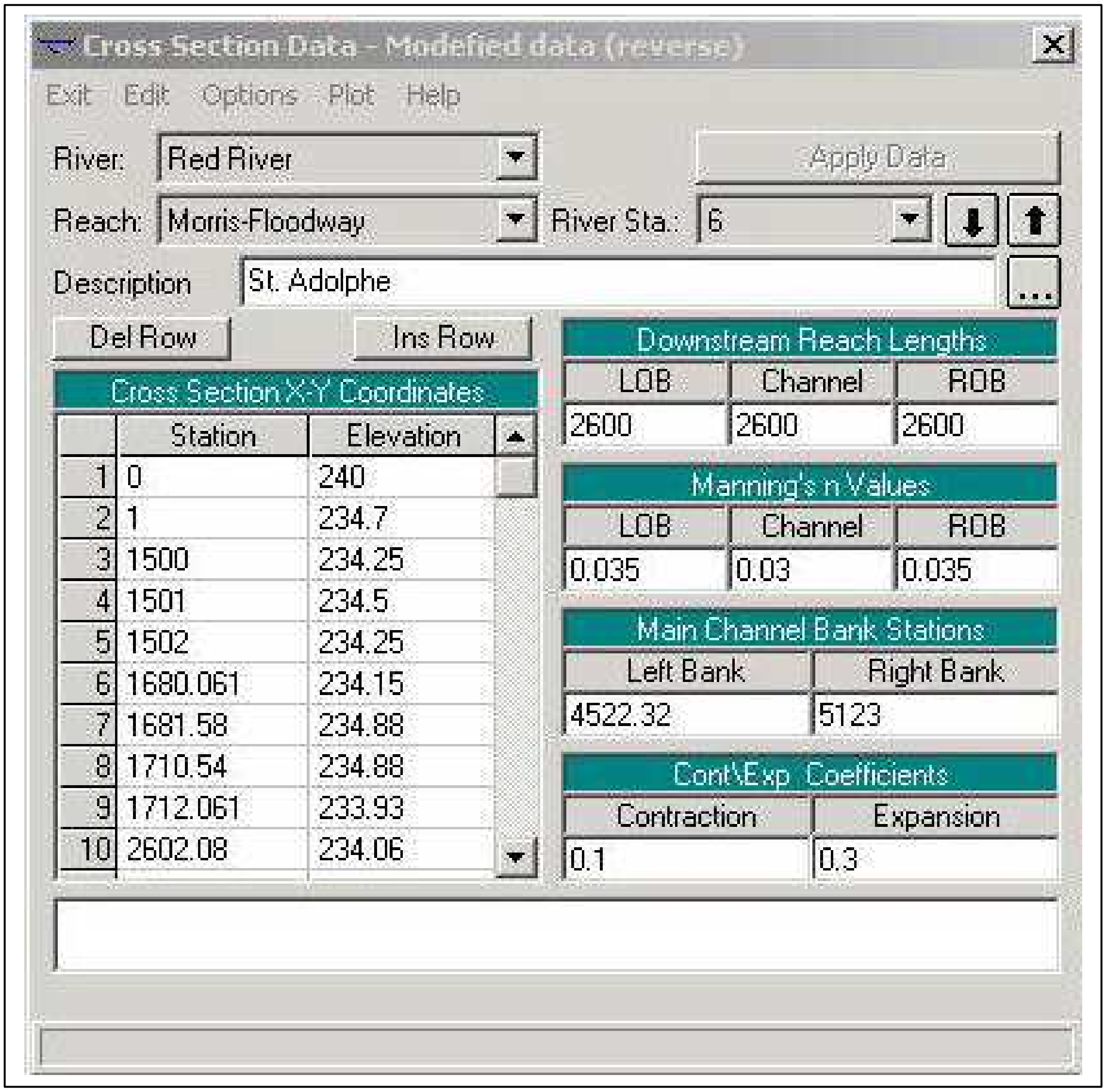


Figure B3: Cross section data window in HEC-RAS

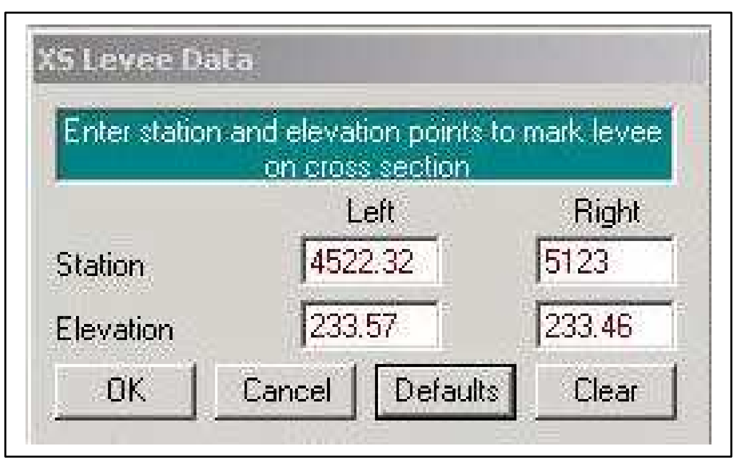
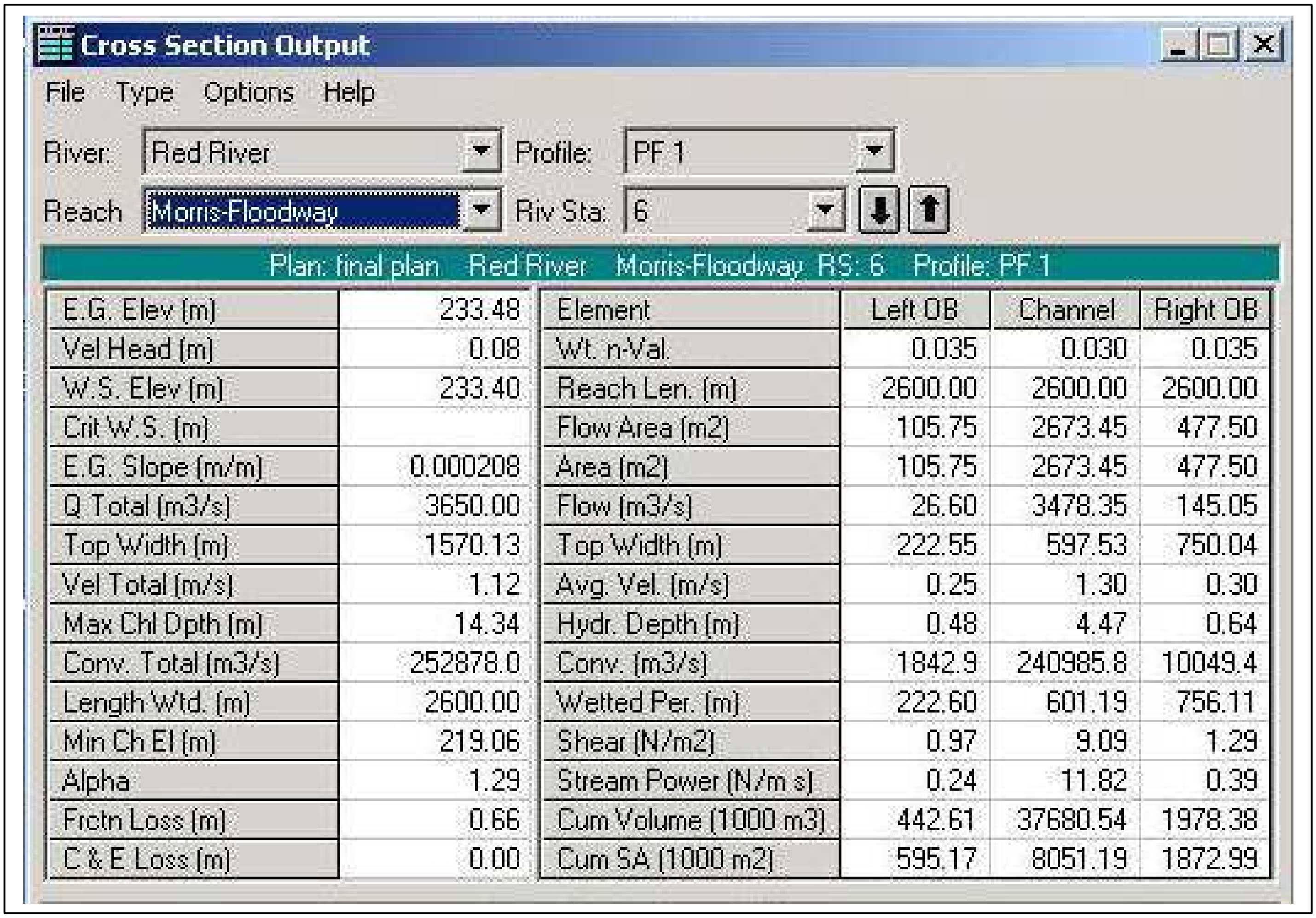


Figure B4: Data entry for levee at St. Adolphe



E.G. Elev (m)	233.48
Vel Head (m)	0.08
W.S. Elev (m)	233.40
Crit W.S. (m)	
E.G. Slope (m/m)	0.000208
Q Total (m3/s)	3650.00
Top Width (m)	1570.13
Vel Total (m/s)	1.12
Max Chl Dpth (m)	14.34
Conv. Total (m3/s)	252878.0
Length Wtd. (m)	2600.00
Min Ch El (m)	219.06
Alpha	1.29
Frctn Loss (m)	0.66
C & E Loss (m)	0.00

Element	Left OB	Channel	Right OB
Wt. n-Val.	0.035	0.030	0.035
Reach Len. (m)	2600.00	2600.00	2600.00
Flow Area (m2)	105.75	2673.45	477.50
Area (m2)	105.75	2673.45	477.50
Flow (m3/s)	26.60	3478.35	145.05
Top Width (m)	222.55	597.53	750.04
Avg. Vel. (m/s)	0.25	1.30	0.30
Hydr. Depth (m)	0.48	4.47	0.64
Conv. (m3/s)	1842.9	240985.8	10049.4
Wetted Per. (m)	222.60	601.19	756.11
Shear (N/m2)	0.97	9.09	1.29
Stream Power (N/m s)	0.24	11.82	0.39
Cum Volume (1000 m3)	442.61	37680.54	1978.38
Cum SA (1000 m2)	595.17	8051.19	1872.99

Figure B5: Cross section output at river station 6.

APPENDIX C - Description of GIS Procedure

Computation of Flood Water Depth

Determine the spatial extents of the floodwater resulting from implementation of the various flood protection alternatives. GIS and Image Processing software (Idrisi32, 2001) was used to carry out computation of floodwater depth using GIS data described in the main report. Basic data files needed for floodwater depth in the region of interest are:

- DEM of the area of interest.
- Feature images of buildings, roads and agriculture.
- Water surface elevation value for each alternative obtained from HEC-RAS simulations.

GIS modules mentioned in capitals in the steps below were used for each particular step.

1. Assign water surface elevations to the river reach in the feature image using 'ASSIGN'.
2. Subtract the ground surface elevation as contained in the DEM from the water surface elevation, which will determine the depth of submergence using 'OVERLAY'.
3. Create a Boolean mask of locations having a ground elevation less than the water surface elevation using 'RECLASS'.
4. Find all contiguous groups in the mask using 'GROUP'.
5. Select the flooded group based on the location of the main stem of the Red River using 'EXTRACT'.
6. Create a values file containing the flooded group identifier using 'ASSIGN'.
7. Create an image of just the flooded group using 'ASSIGN'.
8. Overlay the flooded group under the feature image using 'OVERLAY'.
9. Convert the flood Boolean mask to byte binary file type using 'CONVERT'.
10. Create Boolean image of the Red River and its tributaries using 'RECLASS'.

11. Subtract river Boolean from flood Boolean mask using ‘OVERLAY’.
12. Eliminate any negative numbers from rounding in the flooded area mask using RECLASS’.
13. Multiply flooded area mask with depth of submergence to get the “flood water depth” criteria using ‘OVERLAY’.
14. Replace the cell values in above created image with the value of minimum floodwater depth in above image to get ‘best floodwater depth’ image using ‘RECLASS’.
15. Replace the cell values in image created in Step # 13 with the value of maximum floodwater depth in above image to get ‘worst floodwater depth’ image using ‘RECLASS’.

Computation of Damages

Determining the percent damages to buildings produced through the implemented alternative. GIS and Image Processing software (Idrisi32, 2001) is used to carry out computation of damages using GIS data described in the main report. Basic data files needed for floodwater depth in the region of interest are:

- DEM of the area of interest.
- Feature images of buildings, roads and agriculture.
- Water surface elevation value for each alternative obtained from HEC-RAS simulations.

GIS modules mentioned in capitals in the steps below were used for each particular step.

1. Create Boolean mask of industrial buildings/roads/agricultural fields using ‘RECLASS’.
2. Multiply flooded area mask with building/roads/agricultural fields mask. This identifies the potentially submerged buildings/roads/agricultural fields, or building/roads/agricultural fields having a ground elevation less than the water surface elevation using ‘OVERLAY’.

3. Multiply the potentially submerged building/roads/agricultural fields by the DEM. This produces the image, which contains the ground elevations of the potentially submerged building/roads/agricultural fields using ‘OVERLAY’.
4. Subtract the building/roads/agricultural fields elevations from the floodwater surface elevation. This identifies the depth of flooding in each of the potentially submerged building/roads/agricultural fields using ‘OVERLAY’.
5. Determine the number of potentially submerged building/roads/agricultural fields. Each potentially submerged building is given a unique identifier in the image created in above step using ‘GROUP’.
6. Extract the flooded depths of the potentially submerged building/roads/agricultural fields and place them in a values file with the corresponding building/roads/agricultural fields identifier using ‘EXTRACT’.
7. Apply damage relationships for each category of buildings, roads and agricultural fields using ‘IMAGE CALCULATOR’.
8. 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 using ‘ASSIGN’.
9. Identify the total number/length of flooded buildings/agricultural fields/roads. The image will show each flooded building/agricultural field/road with a unique identifier using ‘GROUP’.
10. Find out the number of cells composing each building/agricultural field/road. The locations/cells of the damaged buildings contain the number of cell, which compose each of the flooded building/agricultural field/road using ‘AREA’.
11. By dividing the damages to the whole building/agricultural field/road by the building/agricultural field/road area an image will be produced in which each cell contains the $ value of damage for each individual building cell using ‘OVERLAY’.
12. Add three images of building damage, agricultural damage and road damage using ‘OVERLAY’.
13. Replace the cell values in damage image created in Step # 12, with the value of minimum damage value to get ‘optimal damage’ image using ‘RECLASS’.

14. Replace the cell values in damage image created in Step # 12, with the value of maximum damage value to get ‘optimal damage’ image using ‘RECLASS’.

Compromise Programming

Actual, best and worst images of both the criteria ‘floodwater depth’ and ‘damage’ have been obtained in the procedures described above. Three weight sets are given in Table 2. Substituting the value of ‘$p=2$’ and weights given in weight set # 1, three distance metric images were computed by applying Equation (2) for all the three alternatives separately using ‘IMAGE CALCULATOR’. Similar distance metric images were obtained using weight set # 2 and weight set # 3.

Ranking of Alternatives

The distance metric images of all the three alternatives for weight set # 1 were ranked using ‘MDCHOICE’. This produced an image of spatially ranked alternatives on a cell by cell basis. Similarly two more spatially ranked alternatives’ images were obtained for weight set # 2 and weight set # 3.

APPENDIX D – MATLAB Procedure

Fuzzification of criteria images and subsequent computations for Spatial Fuzzy Compromise Programming using fuzzy arithmetic were carried out using MATLAB. Triangular membership function and Z-shaped membership functions were used for fuzzification. Following MATLAB codes were developed for the same. Code 1 'script_dm' is the main script that takes the inputs of fuzzified images from Code 2 'dike', Code 3 'floodway_1' and Code 4 'floodway_2' and defuzzifies them. Therefore, the outputs from Code 1 are defuzzified image display and image data files in ASCII format for each of the three alternatives. These output image files are then taken to GIS software for ranking. Code 2 'dike', Code 3 'floodway_1' and Code 4 'floodway_2' transform the criteria value images for three alternatives respectively into fuzzified form by applying desired membership function. The inputs to these codes are images derived from GIS procedure for floodwater depth (best, worst and actual scenario) and damages (best, worst and actual scenario). The computations for fuzzified distance metric are carried out using fuzzy arithmetic resulting in a fuzzified image of distance metric for alternative 'Dike', 'Floodway 1' and Floodway 2' respectively. Code 5 'fuzzyImage' is a function recalled by Codes 2, 3 and 4 to fuzzify any image using triangular membership function. Parameter 'a' specifies the center value of triangular function and parameters 'p1' and 'p2' are the deviation extents towards the left and right side of triangular function respectively. Code 6 'fuzzyImageArith' is a function recalled by Codes 2, 3 and 4 to carry out the fuzzy arithmetic computations (add, subtract, multiply, divide and power) between two fuzzy numbers for triangular membership function. Code 7 'fuzzyIntArith' carries out the computations of fuzzy arithmetic between two fuzzy numbers using fuzzy interval arithmetic. Code 8 'trifn' applies the triangular membership function to fuzzify an image and is recalled by Code 5. Code 9 'fuzzyImageFuzzyNumber' takes an image A and a fuzzy number B and wither raises the image to the power of the fuzzy number or multiplies the image by the fuzzy number. This function is recalled by Codes 2, 3 and 4. Code 10 'difuzImage' is a function that defuzzifies an image A giving 'x1' importance to decision maker's preference. This function is being recalled by Code 1. Code 11 ‘fuzzifyImageZ-MF’ is a function that fuzzifies an image using Z-shaped membership function taking ‘a’ as pixel value in the image and ‘p1’ and ‘p2’ as extreme slope values required in Z membership function. Code 12 ‘fuzzyArithZ-MF’ function carries out fuzzy arithmetic computation for the case of Z membership function. This function is recalled by Codes 2, 3 and 4 in the case of Z membership function computations. Code 13 ‘fuzzyImagePowerZ-MF’ is a function recalled by Codes 2, 3 and 4 to carry out fuzzy image and fuzzy number operations (multiply and power) for the case of Z membership function.

Code 1 – script_dm

```
%   Script to execute the fuzzification of criteria iamges and parameters to compute
%   fuzzified distance metrics for all the three alternatives and then defuzzify and
%   plot each of the distance metrics. Also saves ascii  raster data file of each alternative
%   distance metric for importing them to IDRISI for ranking purpose.
%   Developed by Nirupama in April, 2002

global m; global n; global n_point; global alpha;

%   Alternative Dike

fuzzydike_total_Z-MF_w1;
fuzzy_dike_Z-MF_w1 = fuz_dike;
dike_Z-MF_w1_trifn = defuzZ-MF(fuzzy_dike_Z-MF_w1,0.5);
save dike_w1.dat dike_Z-MF_w1 –ascii        %  save defuzzified image in ASCII format

figure              %   Display the defuzzified image
imagesc(dike_Z-MF_w1);
title ('Dike Z-MF for weight set # 1')
colorbar

%   Alternative Floodway 1

fuzzyfloodway1_total_Z-MF_w1;
fuzzy_floodway1_Z-MF_w1 = fuz_floodway1;
floodway1_Z-MF_w1 = defuzZ-MF(fuzzy_A2_Z-MF_w1,0.5);
save floodway1_w1.dat floodway1_Z-MF_w1 –ascii          %  save defuzzified image in
                                                        ASCII %  data file

figure              %   Display the defuzzified image
```

```
imagesc(floodway1_Z-MF_w1);
title ('floodway1 Z-MF for weight set # 1')
colorbar

%   Alternative Floodway 2

fuzzyfloodway2_total_Z-MF_w1;
fuzzy_floodway2_Z-MF_w1 = fuz_floodway2;
floodway2_Z-MF_w1 = defuzZ-MF(fuzzy_A3_Z-MF_w1,0.5);
save floodway2_w1.dat floodway2_Z-MF_w1 –ascii          %  save defuzzified image in
                                                         ASCII %  data file

figure              %   Display the defuzzified image
imagesc(floodway2_Z-MF_w1);
title ('floodway2 Z-MF for weight set # 1')
colorbar
```

Code 2 – dike

```
%   Compute fuzzified images for alternative 'Dike'
%   Created by Nirupama in April, 2002


% read crieriion 'flood depth' actual scenario image

load dike_flood_new.txt
d1 = dike_flood_new;
d1 = fuzzifyImageZ-MF(d1,0.005,1);

% read criteria 'flood depth' worst scenario image

load dike_flood_worst_new.txt
d2 = dike_flood_worst_new;
d2 = fuzzifyImageZ-MF(d2,1,1);

% read criteria 'flood depth' the best scenario image

load dike_flood_optimal_new.txt
d3 = dike_flood_optimal_new;
d3 = fuzzifyImageZ-MF(d3,0.005,1);

%   Read criteria 'damage' the actual scenario image
```

```
load dike_total_damage.txt
d4 = dike_total_damage;
d4 = fuzzifyImageZ-MF(d4,10000,10000);

%   Read criteria 'damage' the worst scenario image

load dike_total_damage_worst.txt
d5 = dike_total_damage_worst;
d5 = fuzzifyImageZ-MF(d5,10000,10000);

%   Read criteria 'damage' the best scenario image

load dike_total_damage_optimal.txt
d6 = dike_total_damage_optimal;
d6 = fuzzifyImageZ-MF(d6,10000,10000);

%   Assign fuzzified weight set # 1 to criteria

w1 = sigmf(alpha, [.01 .5 .5 1]);    %w1 = 0.5
w2 = sigmf(alpha, [.01 .5 .5 1]);    %w2 = 0.5

%   Assign fuzzified weight set # 2 to criteria

w1 = trifn(.05,.1,.15);
w2 = trifn(.85,.9,.95);

%   Assign fuzzified weight set # 3 to criteria

w1 = trifn(.85,.9,.95);
w2 = trifn(.05,.1,.15);

%   Fuzzifiy parameter 'p' and '1/p'

p = trifn(1,2,2);
one = trifn(0.95,1,1.05);
one_over_p = fuzzyIntArith(one,p, 'divide');

%   Compute fuzzified distance metric using fuzzy arithmetic

dn1_1 = abs(fuzzyArithZ-MF(d2,d1, 'subtract'));
dn1_2 = abs(fuzzyArithZ-MF(d3,d2, 'subtract'));
dn1 = fuzzyArithZ-MF(dn1_1,dn1_2, 'divide');

dn2_1 = abs(fuzzyArithZ-MF(d5,d4, 'subtract'));
dn2_2 = abs(fuzzyArithZ-MF(d6,d5, 'subtract'));
```

```
dn2 = fuzzyArithZ-MF(dn2_1,dn2_2, 'divide');

%   For weight set # 1 (when 'sigmf' is applied
%   to fuzzifiy the weights

% temp1 = fuzzyArithPowerZ-MF(w1,p(i), 'power');
% temp12 = fuzzyArithPowerZ-MF(w2,p(i), 'power');

%   For weight set # 2 and 3 (when 'trifn' is applied
%   to fuzzifiy the weights

temp1 = fuzzyIntArith(w1,p, 'power');
temp12 = fuzzyIntArith(w2,p, 'power');

%   Final computations for distance metric

temp2 = fuzzyArithPowerZ-MF(dn1,one_over_p, 'power');
temp3 = fuzzyArithPowerZ-MF(dn2,one_over_p, 'power');

temp4 = fuzzyArithPowerZ-MF(temp2, temp1, 'multiply');
temp5 = fuzzyArithPowerZ-MF(temp3, temp12, 'multiply');

fuz_dike = fuzzyArithZ-MF(temp4, temp5, 'add');    %  output fuzzy image
```

Code 3 – floodway_1

```
%   Compute fuzzified images for alternative 'Floodway 1'
%   Created by Nirupama in April, 2002


% read crieriion 'flood depth' the actual scenario image

load floodway1_flood_new.txt
d1 = floodway1_flood_new;
d1 = fuzzifyImageZ-MF(d1,0.005,1);

% read criteria 'flood depth' the worst scenario image

load floodway1_flood_worst_new.txt
d2 = floodway1_flood_worst_new;
d2 = fuzzifyImageZ-MF(d2,1,1);

% read criteria 'flood depth' the best scenario image
```

```
load floodway1_flood_optimal_new.txt
d3 = floodway1_flood_optimal_new;
d3 = fuzzifyImageZ-MF(d3,0.005,1);

%   Read criteria 'damage' the actual scenario image

load floodway1_total_damage.txt
d4 = floodway1_total_damage;
d4 = fuzzifyImageZ-MF(d4,10000,10000);

%   Read criteria 'damage' the worst scenario image

load floodway1_total_damage_worst.txt
d5 = floodway1_total_damage_worst;
d5 = fuzzifyImageZ-MF(d5,10000,10000);

%   Read criteria 'damage' the best scenario image

load floodway1_total_damage_optimal.txt
d6 = floodway1_total_damage_optimal;
d6 = fuzzifyImageZ-MF(d6,10000,10000);

%   Assign fuzzified weight set # 1 to criteria

w1 = sigmf(alpha, [.01 .5 .5 1]);    %w1 = 0.5
w2 = sigmf(alpha, [.01 .5 .5 1]);    %w2 = 0.5

%   Assign fuzzified weight set # 2 to criteria

w1 = trifn(.05,.1,.15);
w2 = trifn(.85,.9,.95);

%   Assign fuzzified weight set # 3 to criteria

w1 = trifn(.85,.9,.95);
w2 = trifn(.05,.1,.15);

%   Fuzzifiy parameter 'p' and '1/p'

p = trifn(1,2,2);
one = trifn(0.95,1,1.05);
one_over_p = fuzzyIntArith (one,p, 'divide');

%   Compute fuzzified distance metric using fuzzy arithmetic
```

```
dn1_1 = abs(fuzzyArithZ-MF(d2,d1, 'subtract'));
dn1_2 = abs(fuzzyArithZ-MF(d3,d2, 'subtract'));
dn1 = fuzzyArithZ-MF(dn1_1,dn1_2, 'divide');

dn2_1 = abs(fuzzyArithZ-MF(d5,d4, 'subtract'));
dn2_2 = abs(fuzzyArithZ-MF(d6,d5, 'subtract'));
dn2 = fuzzyArithZ-MF(dn2_1,dn2_2, 'divide');

%   For weight set # 1 ('sigmf' is applied
%   to fuzzifiy the weights)

% temp1 = fuzzyArithPowerZ-MF(w1,p(i), 'power');
% temp12 = fuzzyArithPowerZ-MF(w2,p(i), 'power');

%   For weight set # 2 and 3 ('trifn' is applied
%   to fuzzifiy the weights)

temp1 = fuzzyIntArith(w1,p, 'power');
temp12 = fuzzyIntArith(w2,p, 'power');

%   Final computations for distance metric

temp2 = fuzzyArithPowerZ-MF(dn1,one_over_p, 'power');
temp3 = fuzzyArithPowerZ-MF(dn2,one_over_p, 'power');

temp4 = fuzzyArithPowerZ-MF(temp2, temp1, 'multiply');
temp5 = fuzzyArithPowerZ-MF(temp3, temp12, 'multiply');

fuz_floodway1 = fuzzyArithZ-MF(temp4, temp5, 'add');     %  output fuzzified image
```

Code 4 – floodway_2

```
%   Compute fuzzified distance metric for alternative ‘Floodway 2’
%   Created by Nirupama in April, 2002


% read crieriion 'flood depth' the actual scenario image

load floodway2_flood_new.txt
d1 = floodway2_flood_new;
d1 = fuzzifyImageZ-MF(d1,0.005,1);

% read criteria 'flood depth' the worst scenario image
```

```
load floodway2_flood_worst_new.txt
d2 = floodway2_flood_worst_new;
d2 = fuzzifyImageZ-MF(d2,1,1);

% read criteria 'flood depth' the best scenario image

load floodway2_flood_optimal_new.txt
d3 = floodway2_flood_optimal_new;
d3 = fuzzifyImageZ-MF(d3,0.005,1);

%   Read criteria 'damage' the actual scenario image

load floodway2_total_damage.txt
d4 = floodway2_total_damage;
d4 = fuzzifyImageZ-MF(d4,10000,10000);

%   Read criteria 'damage' the worst scenario image

load floodway2_total_damage_worst.txt
d5 = floodway2_total_damage_worst;
d5 = fuzzifyImageZ-MF(d5,10000,10000);

%   Read criteria 'damage' the best scenario image

load floodway2_total_damage_optimal.txt
d6 = floodway2_total_damage_optimal;
d6 = fuzzifyImageZ-MF(d6,10000,10000);

%   Assign fuzzified weight set # 1 to criteria

w1 = sigmf(alpha, [.01 .5 .5 1]);    %w1 = 0.5
w2 = sigmf(alpha, [.01 .5 .5 1]);    %w2 = 0.5

%   Assign fuzzified weight set # 2 to criteria

w1 = trifn(.05,.1,.15);
w2 = trifn(.85,.9,.95);

%   Assign fuzzified weight set # 3 to criteria

w1 = trifn(.85,.9,.95);
w2 = trifn(.05,.1,.15);

%   Fuzzifiy parameter 'p' and '1/p'
```

```
p = trifn(1,2,2);
one = trifn(0.95,1,1.05);
one_over_p = fuzzyIntArith(one,p, 'divide');

%   Compute fuzzified distance metric

dn1_1 = abs(fuzzyArithZ-MF(d2,d1, 'subtract'));
dn1_2 = abs(fuzzyArithZ-MF(d3,d2, 'subtract'));
dn1 = fuzzyArithZ-MF(dn1_1,dn1_2, 'divide');

dn2_1 = abs(fuzzyArithZ-MF(d5,d4, 'subtract'));
dn2_2 = abs(fuzzyArithZ-MF(d6,d5, 'subtract'));
dn2 = fuzzyArithZ-MF(dn2_1,dn2_2, 'divide');

%   For weight set # 1 (when 'sigmf' is applied
%   to fuzzifiy the weights

% temp1 = fuzzyArithPowerZ-MF(w1,p(i), 'power');
% temp12 = fuzzyArithPowerZ-MF(w2,p(i), 'power');

%   For weight set # 2 and 3 (when 'trimf' is applied
%   to fuzzifiy the weights

temp1 = fuzzyIntArith(w1,p, 'power');
temp12 = fuzzyIntArith(w2,p, 'power');

%   Final computations for distance metric

temp2 = fuzzyArithPowerZ-MF(dn1,one_over_p, 'power');
temp3 = fuzzyArithPowerZ-MF(dn2,one_over_p, 'power');

temp4 = fuzzyArithPowerZ-MF(temp2, temp1, 'multiply');
temp5 = fuzzyArithPowerZ-MF(temp3, temp12, 'multiply');

fuz_floodway2 = fuzzyArithZ-MF(temp4, temp5, 'add');     % output fuzzified image
```

Code 5 – fuzzyImage

```
function A=fuzzifyImage(a,p1,p2)

%   fuzzyifyImage fuzzifies an Image (Matrix)
```

```
global m; global n; global n_point;
[n,m]=size(a);
n_point = n*m;
% takes the matrix, and converts it into a vector, col by col

b=reshape(a, 1, n_point);
bmin = min(b(find(b)));
bmax = max(b(find(b)));

global alpha;
alpha=(linspace(0,1, 11))';

% to store all fuzzified results into a big matrix
num_row=length(alpha);
num_col=length(b)*2;

resultM=zeros(num_row, num_col);

for i=1:length(b),
  if b(i) == 0,
    B=trifn(0,0.001,0.002);
  else
    B=trifn(b(i)-p1,b(i),b(i)+p2);
  end
  resultM(:,i+(i-1):(i+i))=B;

end

A=resultM;
```

Code 6 – fuzzyImageArith

```
function C=fuzzyImageArith(A,B,operator)

%   FUZZYIMAGEARITH Fuzzy Arithmetic performed on
%   images that are fuzzified

[nA,mA]=size(A);
[nB,mB]=size(B);

% C is the resultant image
C_ResTemp=zeros(nA,mA);
```

```
global alpha;

if (nA~=nB) | (mA~=mB),
   disp('Sizes of input parameters do not match');
   break;
end

% to perform fuzzy addition
% mA/2 is the amount to fuzzy numbers present
for i=1:(mA/2),
   xAL=A(:,i+(i-1));
   xAR=A(:,i+i);

   xBL=B(:,i+(i-1));
   xBR=B(:,i+i);

   if strcmp(operator, 'add'),
      xCL=xAL+xBL;
      xCR=xAR+xBR;
      C_temp=[xCL xCR];
      C_ResTemp(:,i+(i-1):(i+i))=C_temp;
   elseif strcmp(operator, 'subtract'),
      xCL=xAL-xBR;
      xCR=xAR-xBL;
      C_temp=[xCL xCR];
      C_ResTemp(:,i+(i-1):(i+i))=C_temp;
   elseif strcmp(operator, 'multiply'),
      tmp=[xAL.*xBL xAL.*xBR xAR.*xBL xAR.*xBR];
      tmp=tmp'; %because max operator finds max of column of a matrix
      xCL=min(tmp)';
      xCR=max(tmp)';
      C_temp=[xCL xCR];
      C_ResTemp(:,i+(i-1):(i+i))=C_temp;
   elseif strcmp(operator, 'divide'),
      tmp=[xAL./xBL xAL./xBR xAR./xBL xAR./xBR];
      tmp=tmp'; %because max operator finds max of column of a matrix
      xCL=min(tmp)';
      xCR=max(tmp)';

      % this is the index of the non-finite (i.e. inf or -inf) entries
      indexL=find(~finite(xCL));
      indexR=find(~finite(xCR));

      % if the fuzzy number B contains zero in its interval,
      % the program will terminate becasue the resulting fuzzy
```

```
    % number will not be valid
    if (~isempty(indexL)) | (~isempty(indexL)),
      disp('*************************************************');
       disp('*The fuzzy number B contains zero in its interval*');
      disp('*************************************************');
      break;
    else
      C_temp=[xCL xCR];
      C_ResTemp(:,i+(i-1):(i+i))=C_temp;
    end


  elseif strcmp(operator, 'power'),
     tmp=[xAL.^xBL xAL.^xBR xAR.^xBL xAR.^xBR];
     tmp=tmp'; %because max operator finds max of column of a matrix
    xCL=min(tmp)';
    xCR=max(tmp)';
    C_temp=[xCL xCR];
    C_ResTemp(:,i+(i-1):(i+i))=C_temp;
  end

end

C=C_ResTemp;
```

Code 7 – fuzzyIntArith

```
function C=fuzzyIntArith(A,B,operator)

%   FUZZYINTARITH Fuzzy Arithmetic calculated by interval arithmetic

[nA,mA]=size(A);
[nB,mB]=size(B);

global alpha;

if (nA~=nB) | (mA~=mB),
  disp('Sizes of input parameters do not match');
  break;
end

% first column of A is xLeft, second is xRight
```

```
xAL=A(:,1);
xAR=A(:,2);

xBL=B(:,1);
xBR=B(:,2);

% the following statements perform interval arithmetic
if strcmp(operator, 'add'),
  xCL=xAL+xBL;
  xCR=xAR+xBR;
  C=[xCL xCR];

elseif strcmp(operator, 'subtract'),
  xCL=xAL-xBR;
  xCR=xAR-xBL;
  C=[xCL xCR];

elseif strcmp(operator, 'multiply'),
  tmp=[xAL.*xBL xAL.*xBR xAR.*xBL xAR.*xBR];
  tmp=tmp'; %because max operator finds max of column of a matrix
  xCL=min(tmp)';
  xCR=max(tmp)';
  C=[xCL xCR];

elseif strcmp(operator, 'divide'),
  tmp=[xAL./xBL xAL./xBR xAR./xBL xAR./xBR];
  tmp=tmp'; %because max operator finds max of column of a matrix
  xCL=min(tmp)';
  xCR=max(tmp)';

  % this is the index of the non-finite (i.e. inf or -inf) entries
  indexL=find(~finite(xCL));
  indexR=find(~finite(xCR));

  % if the fuzzy number B contains zero in its interval,
  % the program will terminate becasue the resulting fuzzy
  % number will not be valid
  if (~isempty(indexL)) | (~isempty(indexL)),
    disp('**************************************************');
    disp('*The fuzzy number B contains zero in its interval*');
    disp('**************************************************');
    break;
  else
    C=[xCL xCR];
  end
```

```
elseif strcmp(operator, 'power'),
   tmp=[xAL.^xBL xAL.^xBR xAR.^xBL xAR.^xBR];
   tmp=tmp'; %because max operator finds max of column of a matrix
   xCL=min(tmp)';
   xCR=max(tmp)';
   C=[xCL xCR];
end
```

Code 8 – trifn

```
function A=trifn(a,b,c)

%   TRIFN Triangular Fuzzy Number

if (b-a)<0,
   disp('Not valid input - b must be >= a');
   break;
elseif (c-b)<0,
   disp('Not valid input - c must be >= b');
   break;
end

global alpha; % It gets this from FCP.m
% alpha is the column vector from 0 to 1, with small increments

xAL=alpha.*(b-a)+a;
xAR=-1.*alpha.*(c-b)+c;

A=[xAL xAR];
```

Code 9 – fuzzyImageFuzzyNumber

```
function C=fuzzyImageFuzzyNumber(A,B,operator)

%   FUZZYIMAGEFUZZYNUMBER takes an image (A) and a fuzzy number (B),
%   and either raises the image
%   to the power of the fuzzy number or multiplies the image
%   by the fuzzy number
```

```
[nA,mA]=size(A); %the image
[nB,mB]=size(B); %the fuzzy number

% C is the resultant image, same size as A
C_ResTemp=zeros(nA,mA);

global alpha;

% to perform fuzzy addition
% mA/2 is the amount to fuzzy numbers present
for i=1:(mA/2),
  xAL=A(:,i+(i-1));
  xAR=A(:,i+i);

  xBL=B(:,1);
  xBR=B(:,2);

  if strcmp(operator, 'power'),
     tmp=[xAL.^xBL xAL.^xBR xAR.^xBL xAR.^xBR];
     tmp=tmp'; %because max operator finds max of column of a matrix
     xCL=min(tmp)';
     xCR=max(tmp)';
     C_temp=[xCL xCR];
     C_ResTemp(:,i+(i-1):(i+i))=C_temp;
  elseif strcmp(operator, 'multiply'),
     tmp=[xAL.*xBL xAL.*xBR xAR.*xBL xAR.*xBR];
     tmp=tmp'; %because max operator finds max of column of a matrix
     xCL=min(tmp)';
     xCR=max(tmp)';
     C_temp=[xCL xCR];
     C_ResTemp(:,i+(i-1):(i+i))=C_temp;
  end
end

C=C_ResTemp;
```

Code 10 – defuzImage

```
function C=defuzImage(A,x1)

%   DEFUZIMAGE deffuzifies a fuzzy image using
%   Chang and Lee's (1994) OERI method
```

```
[nA,mA]=size(A);

% C is the resultant (crisp) image
C_Temp=zeros(1,mA/2);

global alpha;

global m; global n;

% to perform fuzzy addition
% mA/2 is the amount to fuzzy numbers present
for i=1:(mA/2),
   xAL=A(:,i+(i-1));
   xAR=A(:,i+i);
   C_Temp(i)=(trapz(alpha,xAL))*(x1)+(trapz(alpha,xAR))*(1-x1);
end

C=reshape(C_Temp,n,m);
```

Code 11 – fuzzifyImageZ-MF

```
function A=fuzzifyImageZ-MF(a,p1,p2)

%fuzzyifyImage fuzzifies an Image (Matrix)

global m; global n; global n_point; global alpha;

[n,m]=size(a);
n_point = 11;

% takes the matrix, and converts it into a vector, col by col

b=reshape(a, 1, n*m);
bmin = min(b(find(b)));
bmax = max(b(find(b)));

alpha=(linspace(0,1,n_point))';

% to store all fuzzified results into a big matrix

num_row=length(alpha);
```

```
num_col=length(b);

resultM=zeros(num_row, num_col);

for i=1:length(b),
  if b(i) == 0,
    B=Z-MF(alpha, [0 0.001]);
  else
    B=Z-MF(alpha, [b(i)-p1,b(i)+p2]);
  end
  resultM(:,i)=B;

end

A=resultM;
```

Code 12 – fuzzyArithZ-MF

```
function C=fuzzyArithZ-MF(A,B,operator)

%FUZZYINTARITH Fuzzy Arithmetic calculated by interval arithmetic

[nA,mA]=size(A);
[nB,mB]=size(B);

global alpha;

if (nA~=nB) | (mA~=mB),
  disp('Sizes of input parameters do not match');
  break;
end

% the following statements perform interval arithmetic
if strcmp(operator, 'add'),
  C=A+B;

elseif strcmp(operator, 'subtract'),
  C=A-B;

elseif strcmp(operator, 'multiply'),
  C=[A.*B];
```

```
elseif strcmp(operator, 'divide'),
  if B == 0,
     B = 0.001;
  end
   C=[A./B];

elseif strcmp(operator, 'power'),
  C=[A.^B];
end
```

Code 13 – fuzzyImagePowerZ-MF

```
function C=fuzzyImagePowerZ-MF(A,B,operator)

%   FUZZYIMAGEFUZZYNUMBER takes an image (A) and a
%   fuzzy number (B), and either raises the image
%   to the power of the fuzzy number or multiplies
%   the image by the fuzzy number

[nA,mA]=size(A); %the image
[nB,mB]=size(B); %the fuzzy number

% C is the resultant image, same size as A
C_ResTemp=zeros(nA,mA);

% to perform fuzzy addition
% mA/2 is the amount to fuzzy numbers present
for i=1:(mA),
  xA=A(:,i);
  xB=B(:,1);

  if strcmp(operator, 'power'),
     tmp=[xA.^xB];

     C_ResTemp(:,i)=tmp;
  elseif strcmp(operator, 'multiply'),
     tmp=[xA.*xB];

     C_ResTemp(:,i)=tmp;
  end
end

C=C_ResTemp;
```

APPENDIX E – Data Requirement

SFCP analysis is carried out integrating the components of hydraulic modeling, GIS, and fuzzy set theory. Therefore, there are different types of datasets required to implement the SFCP methodology. Actual file names are enclosed in inverted commas.

Hydraulic Data

1. HEC-RAS project “alternatives.prj”;
2. HEC-RAS plan “alternatives.p06”;
3. HEC-RAS geometry data file “alternatives.g03”; and
4. HEC-RAS flow data file “alternative.fo2”

GIS Data

1. DEM of the region of interest, which is obtained from the DEM of a larger area through a GIS (Idrisi32, 2001) module called ‘WINDOW’ (“dem dolphe win”);
2. Feature images of buildings (“buildings”);
3. Feature image of roads (“roads”); and
4. Feature image of agricultural fields (“agriculture”)

Fuzzy Theory Application Data

GIS images, which are required for the computation of distance metric for the three alternatives are obtained through data processing in GIS environment (Idrisi32, 2001). Point to note here is that same data images are used for deterministic computation of distance metric as well.

1. Images of flood depth (one of the two criteria considered in this study) for alternative ‘Dike’ are obtained as follows: “depth_actual” – the actual scenario; “depth_best” – the best scenario; and “depth_worst” – the worst scenario.

2. Images of total damages (another criterion considered in this study) for alternative 'Dike' are obtained as follows: "dike_total_damage" – the actual scenario; "dike_total_damage_ optimal" – the best scenario; and "dike_total_damage_worst" – the worst scenario.

3. Images of flood depth for alternative 'Floodway 1' for the actual, the best and the worst scenario respectively, are obtained as follows: "moreflow_flood_new", "moreflow_flood_optimal_new" and "moreflow_flood_worst_new".

4. Images of total damages for alternative 'Floodway 1' for the actual, the best and the worst scenario respectively, are obtained as follows: "moreflow_total_damage", "moreflow_total_damage_optimal" and "moreflow_total_damage_worst".

5. Images of flood depth for alternative 'Floodway 2' for the actual, the best and the worst scenario respectively, are obtained as follows: "ReducedFlowFloodDepth", "ReducedFlowFloodDepthOptimal" and "ReducedFlowFloodDepthWorst".

6. Images of total damages for alternative 'Floodway 1' for the actual, the best and the worst scenario respectively, are obtained as follows: "reducedflow_total_damage", "reducedflow_total_damage_optimal" and "reducedflow_total_damage_worst".