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ORIGINAL PAPER

Jason K. Levy

Multiple criteria decision making and decision support systems for flood risk management

Abstract Multiple criteria decision making (MCDM) is a collection of methodologies to compare, select, or rank multiple alternatives that typically involve incommensurate attributes. MCDM is well-suited for eliciting and modeling the flood preferences of stakeholders and for improving the coordination among flood agencies, organizations and affected citizens. A flood decision support system (DSS) architecture is put forth that integrates the latest advances in MCDM, remote sensing, GIS, hydrologic models, and real-time flood information systems. The analytic network process (ANP) is discussed with application to short-term flood management options for the middle reaches of the Yangtze River. It is shown that DSS and MCDM can improve flood risk planning and management under uncertainty by providing data displays, analytical results, and model output to summarize critical flood information.

Keywords Risk management · Decision support systems · Flooding

Introduction

Economic and societal losses due to floods and other extreme weather events are steadily increasing (Easterling et al. 1999). Flood risk management is an extremely complex, multidisciplinary field: there may be hundreds or even thousands of conflicting criteria that must be considered, including tangible factors (monetary costs, infrastructure damage, etc) and intangibles (such as socio-psychological variables). While flood management decisions must often be taken on short notice, and under high uncertainty, the effects of such decisions may have far-reaching consequences (including loss of life, property damage, and large-scale evacuation). Finally, moral and ethical values held by the stakeholders may be as important as technical issues, placing high demands on the decision making process. The field of multiple criteria decision making (MCDM) has long been applied to the planning and management of water resources systems (Haimes and Hall 1974; Hipel 1992).

Multiple criteria decision making is a collection of methodologies to compare, select, or rank multiple alternatives that involve incommensurate attributes. Specifically, MCDM techniques are capable of handling quantitative variables, such as the direct water damage caused to inundated items (buildings and property), qualitative factors (such as the degree of ecological damage), and ordinal rankings (for example, a set of water supply alternatives listed from most to least preferred). Lekuthai and Vongvisessomjai (2001) note that more research is needed to quantify intangible flood damages (anxiety, hardship, etc). While the flood risk management process has been extensively discussed at the national and international levels, more effort is needed to examine the preferences, needs, and ‘‘changing value systems’’ of actors involved in the flood management process (Plate 2002).

This paper discusses advances in MCDM theory and practice, with particular emphasis on flood risk management techniques. Many countries have enacted environmental regulations that require a comprehensive multiple criteria analysis as a part of water resources planning and management. This paper considers the use of MCDM for the analysis and management of large-scale, complex flood risk problems. The field of MCDM is well-suited for eliciting and modeling the flood preferences of stakeholders. This paper reviews MCDM approaches, with particular emphasis on problems with a discrete number of alternatives, collectively referred to as multiattribute decision making (MADM). The analytic network process (ANP) (Saaty 2004), a generalization of the original analytic hierarchy process (Saaty 1980) is put forth in order to assist in the identification of flood alternatives and the selection of appropriate

J. K. Levy
Applied Disaster and Emergency Studies (ADES),
Brandon University,
Brandon, R7A 6A9 MB, Canada
E-mail: jlevy@hawaii.edu

flood actions. There are several ANP applications for flood management including the selection of flood control projects (Willet and Sharda 1991) and river basin planning and management (Raju and Pillai 1999).

Next, the implementation of MCDM techniques through computer technologies is discussed. For the past two decades, decision support system (DSS) for MCDM have been widely applied in the context of water resources planning and management, see for example Hipel (1992), Loucks and da Costa (1991), and Loucks (1996). By integrating data collection, flood monitoring, communications, and computing technology, DSS can greatly enhance coordination among flood agencies, organizations and affected citizens. In addition, a flood MCDM–DSS architecture is put forth. Key components include the flood database, flood modeling functions, and the graphical user interface.

Finally, a DSS for ANP is applied to a complex flood management problem in the middle reaches of the Yangtze River. The 1997–1998 El Niño event strengthened the 1998 summer monsoon in the Yangze River Valley (YRV) leading to large ENSO-related rainfall anomalies. In the YRV, over 670 mm of precipitation occurred from June to August 1998 (Wu et al. 2003), directly or indirectly affecting up to 250 million people and flooding over 50 million acres. The YRV floods of 1998 caused over 3,000 fatalities, large-scale food shortages, significant social disruption, and enormous economic damages (one of the most costly flood events in history).

MCDM for flood risk management

The rapid growth of MCDM over the past three decades is due to a number of factors, including dissatisfaction with conventional “single criterion” methods and the emergence of software and algorithms for solving complex environmental problems. MCDM can help decision makers in a flood management problem to formulate their values and preferences, to quantify these priorities, and to apply them to a particular decision context. This process often involves reconciling quantities that are not commensurate. For example, the units of one attribute (flood protection cost) may be in dollars and those of another (safety) may be in lives lost due to flooding. MCDM techniques are widely used to identify alternatives that are dominated by at least one other alternative (i.e., have poorer values on some criteria, and no better values on another criterion). In general, such dominated (inefficient) alternatives should not be considered further as they fall below the efficient frontier.

The MCDM techniques can be categorized into multiple objective mathematical programming (MOMP) and multiattribute decision making (MADM). MADM applies to a discrete set of explicit alternatives (i.e., when the set of alternatives can be defined by listing its finite, and usually small, members). On the other hand, in MOMP, a set of alternatives is implicitly defined by a set of constraints to be satisfied, resulting in a large (or infinite) set of decision alternatives. MOMP problems are often formulated as linear, integer, or nonlinear mathematical programming problems. For example, multiple objective linear programming selects the best of the efficient solutions using Goal Programming and other procedures (a set of decision variables, constrained to remain within a feasible region, are optimized).

In MADM problems, the highest objective is usually a broadly defined goal which may be broken down into a hierarchy of criteria or objectives, with the lower levels becoming more detailed and measurable, but more conflicting. Performance indicators (also referred to as criteria or attributes) measure the degree to which these objectives are achieved. A critical phase of MADM involves construction of the decision matrix (also called the product matrix, payoff matrix, performance matrix, decision table etc.). As shown in Table 1, entries of this matrix represent scores (ratings) r_{ij} of flood alternatives ($A_1,\ldots,A_m$) with respect to flood criteria ($C_1,\ldots,C_n$). Values ($w_1,\ldots,w_n$) in the top row of Table 1 are the important weights of flood criteria.

A wide variety of MADM techniques have been developed. Utility theory, belonging to the “American School” of decision making is perhaps the most widely known. Utility theory is characterized by axiomatically defined utility functions and elicitation methods that are consistent with a set of assumptions about the preference structure of the decision makers. Second, “outranking methods” from the “European School” produce a (weak) ordering of alternatives and employ pairwise comparisons. PROMETHEE (Brans et al. 1986) and ELECTRE (ELimination Et Choix Traduisant la Realitè) (Roy 1968) are among the most popular “outranking methods”. Specifically, ELECTRE compares two policies at a time and selects one over the other if one alternative is better in most criteria and not unacceptably worse in the remaining criteria. A third group of MADM methods are “regret-based” approaches. Here, alternatives are selected if their worst performance (across scenarios, relative to other alternatives) is better than the worst performance of other alternatives. Goal programming constitutes a fourth approach for MADM methods: the closeness of different alternatives to numerically defined goals is measured. Although goal programming is usually applied to MOMP problems, it can also be used to rank discrete alternatives.

A fifth group of methods use the matrix in Table 1 directly. For example, simple additive weighting scales the Table 1 scores, applies criteria weights, adds the r_{ij} values in each row of the matrix, and selects the top ranked alternative. A related approach is simple product weighting which uses the products of r_{ij} values in each row (instead of summations). Hwang and Yoon (1981) also use Table 1 in the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) approach. Here, the most preferred alternative is not only the shortest Euclidean distance from the ‘ideal’ solution, but also the farthest from the undesirable solution (nadir

Table 1 MADM matrix: alternatives, criteria, and weights

Flood alternatives	Flood weights				
	w_1	w_2	w_3	...	w_n
	Flood decision criteria				
	C_1	C_2	C_3	...	C_n
A_1	r_{11}	r_{12}	r_{13}	...	r_{1n}
A_2	r_{21}	r_{22}	r_{23}	...	r_{2n}
⋮	⋮	⋮	⋮	⋮	⋮
A_m	r_{m1}	r_{m2}	r_{m3}	...	r_{mn}

point), across all criteria. Compromise programming (Zeleny 1982) constitutes a final approach using Table 1, ranking alternatives according to their closeness to the so-called 'utopia' point.

The ANP constitutes a sixth MADM approach. With the ANP, one constructs hierarchies or feedback networks, then makes judgments or performs measurements on pairs of elements with respect to a controlling element to derive relative absolute scales that are then synthesized throughout the structure to select the best alternative. The criteria are pairwise compared with respect to the goal, the subcriteria with respect to their parent criterion, and the alternatives of choice with respect to the last level of subcriteria above them (the covering criteria). Each such set of comparisons yields an absolute scale of priorities. An absolute scale is a special instance of a ratio scale with a constant multiplier equal to one. The absolute scale is invariant under the identity transformation.

The priorities throughout the network structure are synthesized with a weighting and adding process to give the overall priorities for the flood management alternatives under consideration. The ANP transforms a multidimensional scaling problem into a uni-dimensional one. Accordingly, alternatives measured under several criteria possessing different scales can be combined. The ANP, using feedback connections between objectives and alternatives, combines the top-down American school (which is "objective-led") with the bottom-up European school ("alternative-led").

ANP background

The ANP is based on four axioms related to obtaining pairwise comparisons, deriving priorities, and synthesizing them to obtain a ranking of alternatives (Saaty 2000). In making pairwise comparisons of elements with respect to a common property, one inputs judgments into the pairwise comparison matrix from the one to nine ANP fundamental scale (Saaty 1980). The smaller element is considered to be the unit and one estimates how many times more important, preferable or likely (or more generally, "dominant"), the larger element is relative to the smaller. Dominance is often interpreted as importance when comparing the criteria and as preference when comparing the alternatives with respect to the criteria. The set of objects being pairwise compared must be homogeneous. That is, the dominance of the largest object must be less than an order of magnitude more than the smallest one. Elements that differ by more than this range can be clustered into homogeneous groups and those homogeneous groups linked with pivot elements that transit from the smaller to the larger. If actual measures using an existing scale are known, the derived priority scale can be derived directly by simply normalizing them (here, homogeneity is not required).

The general problem of deriving priorities from a matrix of pairwise comparison judgments is to solve for the derived priorities from the matrix $A=(a_{ij})$ where the a_{ij} are judgments from the fundamental one to nine scales as discussed by Saaty (1980, 2000). If $a_{ij}=a_{ik}/a_{kj}$ for all i, j, and k, the matrix is consistent.

$$Aw = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \dots & 1 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = cw \tag{1}$$

In general, such pairwise comparison matrices are not consistent and the priorities are derived from the matrix by solving for its principle eigenvector:

$$\sum_{j=1}^{n} a_{ij} w_j = \lambda_{\max i} \tag{2}$$

where $a_{ji}=1/a_{ij}$ ora_{ij} $a_{ji}=1$ (the reciprocal property), $a_{ij}>0$ (thus A is known as a positive matrix) whose solution, known as the principal right eigenvector, is normalized:

$$\sum_{i=1}^{n} w_i = 1 \tag{3}$$

The derived priorities, w_i, are an absolute scale which does not have (or need) a unit of measurement. This homogeneous system of linear equations $Aw=cw$ has a solution w if c is the principal eigenvalue of A. Synthesizing the derived priorities throughout a hierarchy is accomplished with a weighting and adding process known as hierarchic composition. Let H be a complete hierarchy with h levels. Let B_k be the priority matrix of the kth level, $k=2,\ldots,h$. If W' is the global priority vector of the pth level with respect to some element z in the $(p-1)$st level, then the priority vector W of the qth level $(p < q)$ with respect to z is given by the multilinear form,

$$W = B_q B_{q-1} \ldots B_{p+1} W' \tag{4}$$

The global priority vector of the lowest level with respect to the goal is given by

$$W = B_h B_{h-1} \ldots B_2 W' \tag{5}$$

In general, $W' = 1$. The sensitivity of the bottom level alternatives with respect to changes in the weights of elements in any level can be studied by means of these multilinear forms. Assume a system of N clusters or components, where the elements in each component interact with (or have an impact on) some (or all) of the elements of that component. Assume that component h, denoted by C_h, $h = 1, \ldots, N$, has n_h elements, denoted by

$$e_{h_1}, e_{h_2}, \ldots, e_{h_{n_h}} \tag{6}$$

A priority vector derived from paired comparisons represents the impact of a given set of elements in a component on another element in the system. When an element has no influence on another element, its influence priority is assigned a zero. The priority vectors derived from pairwise comparison matrices are each entered as a part of a column of a "supermatrix," which represents the influence priority of an element on the left of the matrix on an element at the top of the matrix. The general representation of a supermatrix is shown in Fig. 1 below. The detail from one of its matrices, the i, j block, is shown in Fig. 2. This component includes all the priority vectors derived for nodes that are "parent" nodes in the C_i cluster (Saaty 2004).

Interaction in the supermatrix may be measured according to several different criteria. To display and relate the criteria, a separate control hierarchy is established that includes the criteria and their priorities. For each criterion, a different supermatrix of impacts is developed. As discussed in (Saaty 2001), a weighted (stochastic) supermatrix is raised to powers until it converges to the limit supermatrix (convergence is assured by the stochasticity of the columns). The limit supermatrix yields the priorities of all elements in the network, including the priorities of the decision alternatives. ANP can allow rank to reverse with the distributive mode or rank can be preserved (from irrelevant alternatives) with the ideal mode

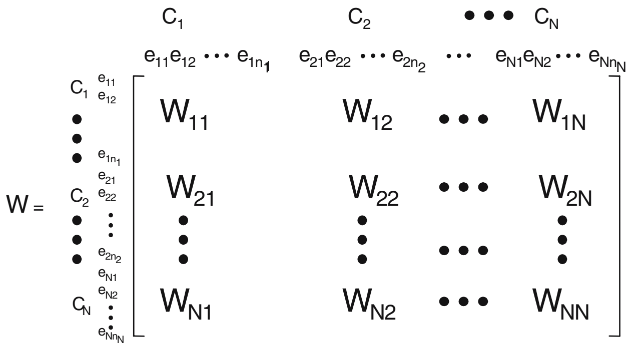

Fig. 1 Supermatrix representation

DSS and MCDM

A DSS is a customized, interactive computing environment that integrates models/analytical tools, databases, graphical user interfaces, and other systems. Sprague (1983) notes that DSS are designed to help decision makers use data and models to evaluate unstructured problems that require management judgment. A number of authors have discussed current and future directions for DSS including Carlsson and Turban (2002), Eom (1999), and Wierzbicki (2000). Important challenges for developing effective DSS in the context of information technology and environmental management (internet security, data ownership, interoperability of computer technologies, etc.) are described by Miller et al. (2004). An extensive literature exists with respect to the use of DSS for water resources planning and management, including water reservoir systems (Loucks 1996; Loucks and da Costa 1991; Soscini-Sessa et al. 2003). Recent developments include the use of object-oriented DSS for environmental MCDM (Dingfei and Stewart 2004).

DSS for flood management dates back more than 35 years, when the US Army Corps of Engineer's (USACE) Hydrologic Engineering Center (HEC) first began developing computer support to evaluate proposed flood damage reduction plans. HEC was established in 1964 and laid the foundations for the field that subsequently became known as hydrologic engineering. The USACE's HEC Flood Hydrograph Package (HEC-1) and Water Surface Profiles program (HEC-2) were released in 1968 to assist with hydrologic and hydraulic analysis respectively. Each decade offered modifications and enhancements of the HEC program. For example, in the late 1980s, USACE mainframe programs were ported to personal computers. Throughout the 1980s, HEC developed DSS for flood control simulation and other water management goals (USACE 1982, 1985, 1986, 1987). The DOS shell menu program "Flood Damage Analysis (FDA) Package on the Microcomputer" assisted with flood data management and information sharing (USACE 1990). In the 1990s, Windows-based graphical user interfaces were used to analyze flood damage reduction alternatives using probabilistic and risk-based approaches (USACE 1997).

A number of DSS exist for flood management, including flood evacuation emergencies (Simonovic and Ahmad 2005), flood risk mitigation and control (Mysiak et al. 2005; Todini 1999; Todini et al. 1997), and social planning (Schielen and Gijsbers 2003). Flood management DSS should be sufficiently flexible that they can assist in the development of long-term water policies as well as short-term flood protection and landscape planning activities. The European Union has developed a number

$$\mathbf{W}_{ij} = \begin{bmatrix} W_{i1}^{(j_1)} & W_{i1}^{(j_2)} & \cdots & W_{i1}^{(jn_j)} \\ W_{i2}^{(j_1)} & W_{i2}^{(j_2)} & \cdots & W_{i2}^{(jn_j)} \\ \vdots & \vdots & & \vdots \\ W_{in_i}^{(j_1)} & W_{in_i}^{(j_2)} & \cdots & W_{in_i}^{(jn_j)} \end{bmatrix}$$

Fig. 2 Details of a component matrix from the Supermatrix

of flood DSS such as the river basin modeling management and flood mitigation (RIBAMOD) project (Casale and Samuels 1998). An overall architecture for flood DSS is shown in Fig. 3, with particular reference to flood reservoir operation and management. The DSS architecture consists of three main components: a flood database, flood modeling functions, and a graphical user interface.

Flood database

The first DSS component is a flood database that typically includes meteorological, hydrogeologic, administrative, and population data. Improved performance of computer technology has led to a growth in the use of remote sensing and GIS techniques. In addition, digital data is easy to process, highly accessible, and less expensive than traditional approaches to the delineation of floodplain boundaries. In 2005, the NOAA-N weather satellite (the fourth in a series of five polar-orbiting weather satellites) was launched in order to collect and transmit additional meteorological data, thereby enhancing databases on climate change and weather modeling (such as El Niño and La Niña climate events). Remotely sensed and hydrological data are often used together with GIS and weather grids for a variety of flood purposes, including flow forecasting, dam control, evacuation simulations, and damage estimation. For example, remotely sensed data that are superimposed over a digital elevation map can facilitate flood depth assessment by using the tonal difference of the floodwater and supervised classification to determine flood depth zones. Spatial flood information is particularly valuable in determining social vulnerability (a function of flood hazard, population, infrastructure at risk, etc.). Islam and Sadu (2002) discuss the use of remote sensing and GIS for flood counter measures.

Current remote sensing tools and methods (weather radar, aircraft measurement, the detection of atmospheric electrical disturbances, rain gages, etc.) provide

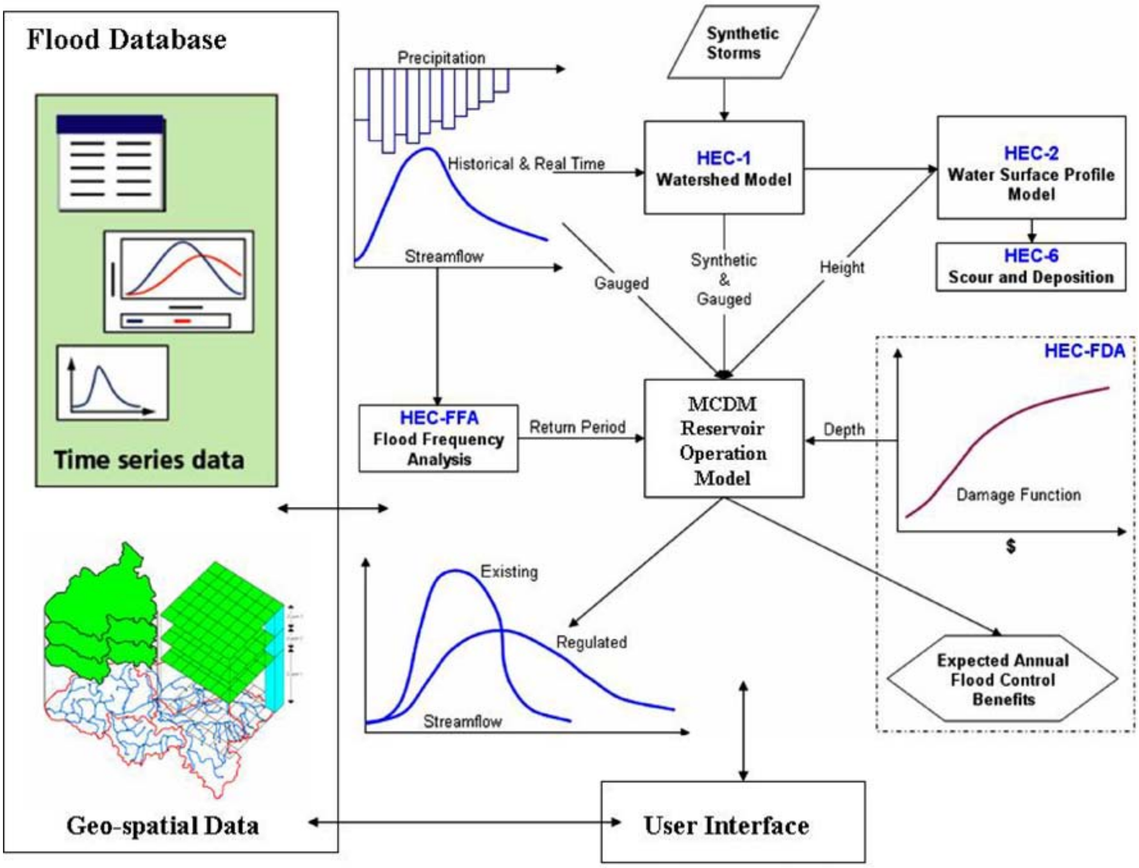

Fig. 3 DSS architecture for reservoir operation (modified from Feldman 1981)

reliable and cost-effective data collection, allowing for continuous, synoptic coverage of snow melt, rainfall, ocean waves, sea-surface height, and other important variables. There are several advantages of remote sensing techniques over ground-based methods, particularly in flood-affected developing countries where there is a low density of gauging stations and a corresponding lack of flood data (Sanyal and Lu 2004). Also, multidate satellite imageries can reconstruct previous flooding events and provide valuable insights into how natural events and anthropogenic activities affect land cover over a period of several years.

The Landsat multispectral scanner (MSS) with 80-m resolution was one of the first satellite remote sensing technologies for flood monitoring and boundary inundation delineation. Early applications involved the flood-prone Mississippi River basin (Deutsch et al. 1973; Rango and Anderson 1974). By the 1980s, the Landsat Thematic Mapper (TM) imageries (with 30-m resolution) became a primary source of flood monitoring and delineation data. Smith (1997) provides a comprehensive review of satellite remote sensing for river inundation: due to the strong absorption of water in the near infrared range of the spectrum, MSS band 7 (0.8–1.1 μm) and Landsat TM NIR (Near Infra-Red) band 4 are valuable for discriminating between water (or moist soil) and dry surfaces. Finally, Wang et al. (2002) propose a combination of Landsat TM band 7 (2.08–2.35 μm) and band 4 to delineate inundated areas in industrial and commercial zones (and other developed areas with asphalt).

At a larger scale, the National Oceanographic and Atmospheric Administration's (NOAA) advanced very high-resolution radiometer (AVHRR) imageries enable near real-time flood monitoring. Drawbacks to monitoring floods with AVHRR include a coarse resolution and sensitivity to weather conditions (clouds, etc.) and satellite viewing angle. Finally, it is often difficult to select an appropriate normalized difference vegetation index (NDVI) threshold in order to distinguish wet from dry surfaces (Wang et al. 2002; Barton and Bathols 1989). However, microwave remote sensing developments, such as synthetic aperture radar (SAR), permit flood monitoring during poor weather conditions (the radar pulse can penetrate cloud cover). A combination of optical and microwave remote sensing technologies have led to flood mapping advances in mountainous areas where most areas appear dark or shaded.

There are three broad approaches for linking models with GIS for improved flood management (Clark 1998). The first approach deals with data processing in the premodeling phase. For example, Zerger and Wealands (2004) note that automated floodplain delineation from digital terrain models, raster-based flood inundation simulation, and the parameterization of flood models all involve preprocessing data into spatial databases. The second approach involves direct GIS support for flood modeling, including flood analysis, calibration, and other tasks. The third approach for integrating GIS and flood models involves postprocessing data. These postprocessing tasks (flood risk mapping, cost-benefit analyses, etc.) have become increasingly ubiquitous in modern flood management (Vermeiran and Watson 2001).

Flood modeling functions

Flood DSS typically contain a suite of flood modeling and decision making functions (scenario analysis, rainfall-runoff simulations, data exploration and assessment, etc.), tailored to the decision makers' needs and expertise (solving spatially explicit flood modeling equations, determining discharge levels, etc.). A variety of sophisticated mathematical approaches have been developed for analyzing complex multivariate flood processes (characterized by correlated random variables such as flood peak, volume, and duration) including probabilistic predictions of inundation recurrence intervals (and magnitudes) and soft computing technologies (fuzzy logic, artificial neural networks, and evolutionary computation).

MCDM modules are particularly valuable for flood decision making. For example, in the context of reservoir operation and management, MCDM can help to analyze the difficult tradeoffs between flood protection (minimize reservoir discharge during peak flood periods) and energy production (meeting a predefined energy production target). Flood protection implies that the reservoir should be kept at as low a level as possible so that the reservoir can accept excess water during flood periods. On the other hand, the energy production objective requires as much water in the reservoir as possible. Thus, a reasonable policy for reservoir operation involves releasing additional water for energy production during low inflow periods and storing part of the peak inflows during flood periods (Stam et al. 1998). Figure 3 illustrates the interrelationships among a number of HEC models in the context of a reservoir operation DSS. For example, HEC-1 results can be used in HEC-2 (water surface profile model), the standard for the US Federal Emergency Management Agency's (FEMA) floodplain evaluations and river channel design. Next, output from HEC-1, HEC-2, HEC-FFA (flood-flow frequency analysis), and HEC-FDA (flood damage assessment) models can serve as input for an MCDM Reservoir Operation Model, which outputs streamflow and expected annual benefits accrued from flood control.

Human–computer interface

The third component of a flood DSS is a rich graphical user interface (GUI) for interactive flood queries, reporting, and display functions. A human–computer interface provides an interactive platform to prioritize alternatives and visualize solutions.

Presenting scientific data in a relevant, easy-to-use format facilitates uncertainty, scenario, and sensitivity analyses. As noted by Frank (1993), "the user interface is the system." Advanced flood display capabilities can be used to help decision makers with a number of important flood management tasks: ascertaining the effects of changes to flood model parameters; manipulating spatial data; creating flood inundation maps; analyzing complicated levee systems; and animating hydrologic and hydraulic phenomena.

A number of graphical user interfaces have been developed for flood DSS. For example, the Java-based HEC-DSSVue is widely used for viewing, plotting, editing, and manipulating data in HEC-DSS database files. It is important to consider the tradeoffs among DSS functionality, efficiency, and required knowledge. Customizable interfaces ensure that the GUI matches the skill level of the flood decision maker (Kingston et al. 2000). Finally, the judicious use of GUIs can facilitate knowledge transfer and increase decision making transparency, thereby improving communication and making the links among knowledge, assumptions, and choices more explicit (Labadie and Sullivan 1986). In short, the nature of interaction between users and the computer system is determined by the interface (Al-Sabhan et al. 2003).

MODSS case study: the Jingjiang flooding problem

This paper applies SuperDecisions, an ANP-based DSS to a flood planning and management problem in the middle reaches of the Yangtze River, China. Asia's worst flooding of 1998 occurred in central China, where monsoon rains continued unabated for much of the summer, particularly in the Yangtze River Basin, affecting up to 250 million people and flooding over 50 million acres. The 1997–1998 El Niño was one of the strongest on record, strengthening the summer monsoon which contributed to the 1998 Yangtze flood event: 670 mm of precipitation occurred in the YRV from June to August, 1998 (Wu et al. 2003). The 1998 Yangtze floods led large-scale food shortages and evacuations, and claimed thousands of lives.

Historically, dikes have been built to control flooding along the Yangtze River, but the 1998 flood levels forced Chinese officials to consider dramatic strategies to save large cities on the Yangtze River from inundation. During the summer of 1998, it was feared that Yangtze River flooding would cause the dikes along the Yangtze to fail to some degree, particularly those already weakened due to erosion, aging, or neglected repairs. To minimize the probability of a catastrophic dike failure in the densely populated city of Wuhan (a city of 7 million inhabitants in China's central Hubei province) and neighboring farmland, Chinese authorities deliberately destroyed dikes in Jianli County (Hubei province), about 90 miles upriver from Wuhan. This preventative action was successful in diverting floodwaters away from Wuhan, lowering the height of the Yangtze River at Wuhan. While this purposeful destruction of dikes at Jianli temporarily prevented Wuhan from being flooded, the social and economic impact on Jianli Country was immense: more than 500,000 people living adjacent to the Yangtze River were forced to evacuate (many on extremely short notice).

However, Chinese officials believed that saving Wuhan from inundation might also require opening floodgates and the deliberate destruction of dikes in the Jingjiang section of the Yangtze River. The Jingjiang flood plain lies in the central Hubei province which is home to over 300,000 people. The Jingjiang flood diversion area had not been used since 1954, when floods killed more than 30,000 people. However, purposefully destroying dikes at Jingjiang would reduce the risk of dikes suddenly bursting at Shashi City. Accordingly, extensive preparations were put in place to dynamite the Jingjiang dikes and divert waters into the Jingjiang floodplain. This was expected to submerge more than 1,000 square kilometers (386 square miles) of land and 27,000–33,000 ha (68,000–82,000 acres) of farmland in the Jingjiang floodplain.

Deliberately flooding towns and villages in the Jingjiang area required the approval of China's State Council. Officials at the Jingjiang Flood Diversion Management Bureau were instructed to begin destroying dikes and opening floodgates when water levels on the Yangtze reached a record high of 45 m (149 feet) at the monitoring station in Shashi city, just north of the area that would be flooded. Fortunately, the water level at the Shashi monitoring station remained approximately 6 cm (2 in.) below the 45-m level. However, as a precautionary measure 330,000 people were evacuated from the Jingjiang region.

ANP modeling

An ANP model has been created using the SuperDecisions software with dependence and feedback for analyzing the Yangtze River flood management problem. The point in time considered is the onset of the 1998 flood, when officials were considering the destruction of dikes at Jianli and Jingjiang. The model was created in order to determine the optimal course of action for decision makers in this flood crisis. Four flood mitigation actions were considered (nodes in the ANP alternatives cluster). First, Chinese officials could evacuate Jianli and destroy the dikes at Jianli, without evacuating or destroying dikes at Jingjiang. In the second alternative, Jianli is evacuated and the Jianli dikes are destroyed. Also, the dikes at Jingjiang are destroyed and the people of Jingjiang are evacuated. In the third alternative, Jianli is evacuated and the Jianli dikes are destroyed (as in the second alternative). However, while Jingjiang is evacuated, the dikes at Jingjiang are not destroyed. In the fourth alternative, dike destruction does not occur in either Jianli or Jingjiang, although Jianli is evacuated as a precautionary measure.

Four additional clusters (economic cluster, environmental cluster, safety cluster, and the social cluster are shown in the ANP decision model of Fig. 4). For example, the safety cluster consists of two nodes: safety with respect to the civilian population and flood rescuers. In Fig. 4, an arrow from one cluster to another means that at least one element in the cluster is connected to elements in the other to form a pairwise comparison set, with comparisons being done for importance or preference with respect to the source element. There is said to be feedback when an arrow goes in both directions between clusters. Figure 4 illustrates the clusters, nodes, and connections in the decision model. A workshop in Wuhan, China, in 2004 was held to determine the preferences for various stakeholders.

The judgments used are from the fundamental scale of the AHP in which one is equally important, three is moderately more important, five is strongly more important, seven is very strongly more important, and nine is extremely more important, with two, four, six, and eight being "between." The complete supermatrix is a 16×16 table with a row and column for each node of the model. The nodes are grouped by cluster, and each pair of clusters is called a component of the supermatrix. Clusters that are connected from a cluster (because nodes are connected) are pairwise compared for influence on the source cluster. The priority vector in the first column of Table 2 is interpreted to mean that the Safety cluster is the most important with 38.6% of the concern followed by the Environment with 24.2%. The value from the cluster matrix that corresponds to a component is multiplied by all of the entries in that component in the supermatrix. The process of multiplying the cluster matrix times the supermatrix in this way results in the weighted supermatrix. The final solution is provided by the limit matrix which is obtained by raising the weighted supermatrix to powers until it converges. The final result is shown in Table 3.

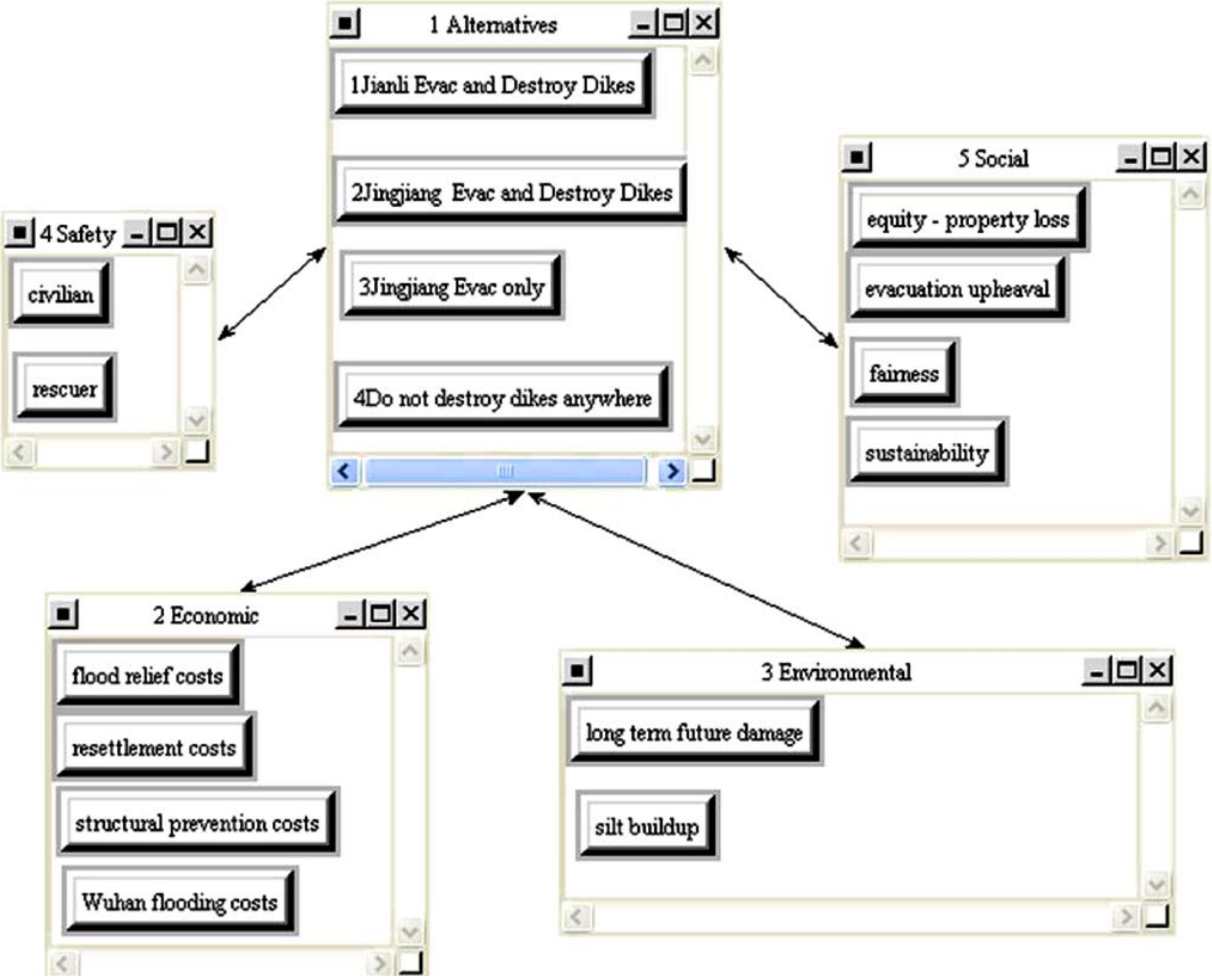

Fig. 4 ANP decision model for the Yangtze flooding problem

Table 2 Cluster matrix

	1 Alternatives	2 Economic	3 Environment	4 Safety	5 Social
1 Alternatives	0.000	1.000	1.000	1.000	1.000
2 Economic	0.168	0.000	0.000	0.000	0.000
3 Environment	0.242	0.000	0.000	0.000	0.000
4 Safety	0.386	0.000	0.000	0.000	0.000
5 Social	0.204	0.000	0.000	0.000	0.000

Table 3 The synthesized results from the Supermatrix

Node name	Limiting values from the Supermatrix	Priorities (limiting values normalized by cluster)
1 Jianli Evac and destroy dikes	0.107489	0.21498
2 Jingjiang Evac and destroy dikes	0.148022	0.29604
3 Jingjiang Evac only	0.142488	0.28498
4 Do not destroy dikes anywhere	0.102002	0.20400
Flood relief costs	0.014876	0.17662
Resettlement costs	0.019280	0.22891
Structural prevention costs	0.006489	0.07704
Wuhan flooding costs	0.043579	0.51742
Long-term future damage	0.063527	0.52580
Silt buildup	0.057292	0.47420
Civilian	0.143855	0.74597
Rescuer	0.048989	0.25403
Equity–property loss	0.028252	0.27667
Evacuation upheaval	0.023996	0.23499
Fairness	0.026297	0.25753
Sustainability	0.023568	0.23080

Table 4 The final priorities for the alternatives of action

1 Jianli Evac and destroy dikes	0.215
2 Jingjiang Evac and destroy dikes	0.296
3 Jingjiang Evac only	0.285
4 Do not destroy dikes anywhere	0.204

The final priorities for the alternative courses of action (extracted from Table 3) are displayed as the final results in Table 4, which shows that the second alternative is the best. This is the situation where both Jianli and Jingjiang are evacuated, and the dikes are also destroyed at both Jianli and Jingjiang. The option that was actually adopted was the third one: to evacuate Jingjiang but not destroy its dikes, having already evacuated Jianli and destroyed the dikes there. The decision makers were fully prepared to implement the model's best choice, but did not do it because the floodwaters stopped centimeters short of the height that would have called for this action.

Conclusions

MCDM is a collection of methodologies to compare, select, or rank multiple alternatives that involve incommensurate attributes. MCDM is well-suited for eliciting and modeling the flood preferences of stakeholders and for improving the coordination among flood agencies, organizations, and affected citizens. A flood DSS architecture is put forth that integrates the latest advances in MCDM, remote sensing, GIS, hydrologic models (rainfall-runoff and models, land surface models, coupled hydrologic, and atmospheric models), real-time flood information systems, social-environmental databases (population statistics, infrastructure data, ecological diversity, river discharge rates, etc.), and graphical user interfaces. This allows for the encapsulation and transfer of knowedge about flood processes. In particular, the use of MCDM for flood risk management can help to facilitate coordination among flood agencies, organizations, and affected citizens in the floodplain. The ANP-based DSS SuperDecisions was used to improve flood decision making for the middle reaches of the Yangtze River. Flood mitigation activities aimed at reducing potentially harmful flood impacts were examined in the context of the historic 1998 flood event.

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