CHAPTER **12**

Working Smarter: Research and Decision Support Systems in Mexican Agriculture

**Philip Heilman, Jeffry Stone, Ignacio Sanchez Cohen,
Hilario Macias Rodriguez, and Roy S. Mann**

CONTENTS

INTRODUCTION

> ***Because technological improvements make workers more productive in manufacturing, wages rise. And they rise not only for manufacturing workers but also for postal workers, teachers, and other service workers… But the technology of personal services is not easily changed. Since it still takes one person to drive a truck and one teacher to teach a class, the cost of these services is forced to rise.***
>
> Baumol and Blinder

ISBN 0-00000-0000/00/

Agricultural research institutions will face many challenges in the 21^{st} century. The importance of producing food and fiber is recognized, and agriculture plays a critical role in rural employment and environmental management. However, agriculture is a mature sector, and research institutions are unlikely to see large budget increases while national budgets are limited. At the same time, research budgets consist largely of salaries for researchers and support personnel. As it takes one person to perform an experiment, budgets are subject to the "cost disease of personal services" identified by Baumol and Blinder (1991, p.7). For many agricultural research institutions, salary costs are increasing faster than budgets, leading to consolidation and reorganization.

In response, agricultural research institutions try to do more with less. There are essentially two options: work harder or work smarter. In the short run, it is possible to make improvements by working harder, but in the long run, organizations are more likely to make sustained progress by "working smarter". The information technology revolution provides a potential source of tools that could help agricultural research institutions work smarter by increasing both the productivity of the agricultural research institutions and the agricultural systems they serve. Computer programs designed explicitly to help people work smarter by making better decisions are called Decision Support Systems (DSS). These tools are clearly no panacea, but in the right situations, they can provide significant benefits. Over time, as the cost of information technology infrastructure continues to decrease, the benefits of providing DSS technology will exceed the cost in more situations, and the role of DSS in agriculture will grow.

This chapter argues that DSS, defined as computer-based information systems designed to help participants in Mexico's agricultural system make better decisions, can play an effective role in improving Mexican agriculture. If agricultural research institutions have a track record of improving efficiency and can point to additional opportunities to improve the agricultural sector, those research institutions can justify a growing budget.

On the other hand, developing Decision Support Systems is expensive and not trivial or easy. Information technology is its own field and requires a different skill set than most agricultural scientists have acquired. To some extent, this is because DSS are an integrator of information and a producer of "secondary" data rather than a generator of primary or source information. Furthermore, skills are required in both computer science and management information systems, so that the software developed is computationally efficient, easy to use, and produces results that "make sense" to those who will use the outcomes to make decisions. The development of software often seems to be a never-ending endeavor, and the time required to anticipate potential problems, maintain and support large software projects is often beyond the scope of research projects.

The theme of this book is that advances in remote sensing and modeling can be applied to improve the overall functioning of an agricultural system. Remote sensing provides a synoptic view of the state of the earth's surface. Simulation models estimate what will happen in the future under different climate and management scenarios. Both remote sensing and modeling over large areas involve the manipulation of massive amounts of data. A DSS can complement remote sensing and modeling by integrating the information and providing the link with decision-makers. DSS can help convert data from remote sensing and models into knowledge that describes the likely results of alternative courses of action, and apply that knowledge in a framework that helps decision-makers.

DSS can have other, less apparent, benefits to agricultural research institutions in addition to directly helping decision-makers. One such benefit is to provide a mechanism to integrate and apply separate technical specialties. Specialization is a key factor in achieving research progress, but it is often difficult to connect research results from disparate fields. As decision support requires looking at the "big picture" there is a natural impetus for integration. A second benefit is that the application of a DSS will reveal crucial knowledge gaps. Stakeholders are naturally interested in paying for, or working through the political process to fund, research that will address those key knowledge gaps.

The objective of this chapter is to describe how research institutions in Mexico can use DSS to apply remote sensing and modeling to improve agriculture. It will also provide some suggestions for lowering the cost of developing DSS. If successful in developing and applying decision support technology, agricultural research institutions will be better able to demonstrate the contribution of their research and consequently be in a stronger position to argue for increasing budgets that will ensure a continuing and strengthened institutional presence.

LITERATURE REVIEW

There is a large and growing literature on decision support systems. As described by Power (2003), much of the initial research was designed to automate report generation with mainframe computers. Influential early books on DSS include those by Keen and Morton (1978) and Bonczek et al. (1981). Holsapple and Whinston (2001), Turban and Aronson (2000), and Marakas (2003) capture the current status and concepts of DSS, while Power (2004) provides a good introductory survey. Most of the early applications were designed to resolve business problems, although at least one early application focused on water quality issues (Bonczek et al., 1976).

Power (2004) defines a DSS as “a class of computerized information system that supports decision-making activities. DSS are interactive computer-based systems and subsystems intended to help decision makers use communications technologies, data, documents, knowledge and/or models to complete decision process tasks.” It is worth emphasizing that to live up to its name, a DSS should support decision-making rather than make decisions. Often the types of decisions that DSS are designed to address take advantage of the ability of computers to manipulate large amounts of data, but also rely on a decision maker’s judgment. Depending on the time frame and the scope for system manipulation, decisions can be classified as operational, tactical, and strategic. In an agricultural context, an operational decision would be how much fertilizer, pesticide, or irrigation water to apply at a given time in a growing season; a tactical decision would be to select a crop within a rotation; and a strategic decision would be to shift from conventional to organic production (Matthews and Stephens, 2002).

Complementing the development of computer systems, the last few decades have seen significant progress in the development and application of decision theory. Primarily as an outgrowth of the field of operations research, decision theory has become much easier to apply to very complex decisions. One of the key advances has been the development of approaches to making decisions with multiple objectives. Keeney and Raiffa (1993), March (1994), and Hammond and Keeney (1999) have written good introductory books on decision theory with application to multiple objective decision-making. Beinat and Nijkamp (1998) present a number of applications of multiobjective theory to land management. Other examples of multiple objective decision-making in natural resources include the application of Saaty’s (1990) Analytic Hierarchy Process, or AHP, to natural resources (Schmoldt et al., 2001) and for watershed management (de Steiguer et al., 2003), and DEFINITE by Janssen and van Herwijnen (1994).

Since the early 1990s, many natural resource applications of DSS have been developed. Compilations of such examples are described in El-Swaify and Yakowitz (1998), AWRA (2001, 2002a, 2002b), Lawrence and Robinson (2002), and Rizzoli and Jakeman (2002). Decision support for natural resources is similar to business applications in that they consist of an interface to frame the problem and to define appropriate decision criteria and feasible options, database and links to models, knowledge bases, or multiobjective decision components. While business DSS are often designed around databases, natural resource DSS often also include spatial databases in a Geographical Information System (GIS) format. Malczewski (1999) provides advice and examples of GIS approaches that directly incorporate multiobjective decision-making. Increasingly, natural resource DSS also include simulation models to assess the possible effects of alternative decisions on the natural system. Shenk and Franklin (2001) advise on the process of developing simulation models for natural resources, while Singh (2003) provides a discussion of the many issues in hydrologic modeling that are central to natural resource decision-making. Motivated by the lack of widespread application of crop models, Matthews and Stephens (2002) discuss the integration of crop models in agricultural decision support to produce improved outcomes. Similarly, Ahuja et al. (2002) describe a number of modeling efforts with a systems approach emphasizing model links to both field experiments and a DSS. McCown et al. (2002) highlight many of the problems experienced by DSS efforts focused on farmers.

A significant difference between natural resource DSS and business DSS is the longer term, provisional nature of natural resource decisions because of the general lack of knowledge about the system being managed. Often there are so many uncertainties associated with natural resource decisions that a tentative decision is made with the understanding that additional information will be collected, and the decision will be reviewed later in the light of new information. When decision makers collect data to test a working hypothesis while implementing a decision, the approach is called "adaptive management". The emphasis with this approach is on "learning by doing" or continual learning about the system being managed. Walters (1986, 2001) provides a good discussion of adaptive management and its role in decision-making and responding to monitoring when there is insufficient time to collect more information, and the risk of trial and error is unacceptable. The implication of adaptive management for decision support is that decisions are not made just once, but rather are continuously refined as part of an ongoing process.

Watersheds provide a good example of a natural resource area in which information for decision-making is typically inadequate. A watershed is a very complex system that is generally poorly understood. Newson (1997) and Brooks et al. (2003) provide good introductions to many watershed management issues. Davenport (2003) discusses watershed planning, and Loucks (1995) addresses DSS issues related to water resources planning. Typically, only some of the system inputs and outputs have been measured. A simulation model is the logical way to understand system interactions, extrapolate from limited data sets, determine which processes need further research, and estimate the effects of alternative management systems. Because of the complexity of watershed processes, a DSS can be a useful complement to a watershed simulation model. According to the National Research Council (1999, p. 134), "given the difficulties of using and interpreting complex natural resource simulation models and data at the watershed scale, it is necessary that we develop decision tools to assist decision makers in watershed management programs and to facilitate transfer of simulation modeling technology."

METHODOLOGY

Bakos (1998, p. 52) noted the early difficulty in harnessing information technology (IT) to improve efficiency: "Amidst the phenomenal IT revolution, several economists have been puzzled to find only modest growth in productivity reflected in the official statistics of the United States economy. The recognition of this 'productivity paradox' is often attributed to Nobel-winning economist Robert Solow, who famously quipped in 1987 that computers can be seen 'everywhere except in the productivity statistics'." Technological advances have continued to increase the power and reduce the cost of computers since Solow wryly noted the apparent failure of IT to increase productivity. Siegele (2003) argues that the IT revolution is maturing, with a shift in focus from rapid technological advance to the application of IT to solve everyday problems.

Earlier technological revolutions, such as railroads and electrical power, also underwent similar periods of limited application until standards were accepted and methods were developed to harness the potential of those technologies. Railroads allowed a huge geographic change in production and consumption by facilitating the transportation of goods. Electricity facilitated the restructuring of factories to support mass production. Information technology has an equal or greater potential to increase productivity, but that potential improvement will not be realized without a similar re-organization of parts of the economic system. Although the earlier technological revolutions substantially increased productivity, these were periods of wrenching change, and there were economic losers as well as winners.

How can agricultural systems be reorganized to take advantage of IT advances to improve decision-making? One obvious place to start is by looking at the decisions currently made in agriculture and asking where better information could lead to better decision-making. Figure 12- 1 shows a very simple model of an agricultural system. For example, agricultural producers grow corn, which is processed into tortillas, which are in turn sold to consumers. Fertilizers and pesticides applied to the corn crop and oil used to lubricate a mill that grinds corn can be washed into streams and cause negative offsite effects by polluting streams and impacting key aquatic habitats. Within each box, there are a number of decisions that must be made, even if only implicitly. A farmer using the same management system year after year is essentially assuming that the system is sustainable, but it might be possible to assess the sustainability of those agronomic practices, as well as their offsite effects using a DSS. For example, is there a significant risk of losing topsoil through accelerated erosion or a risk of lowering water table?

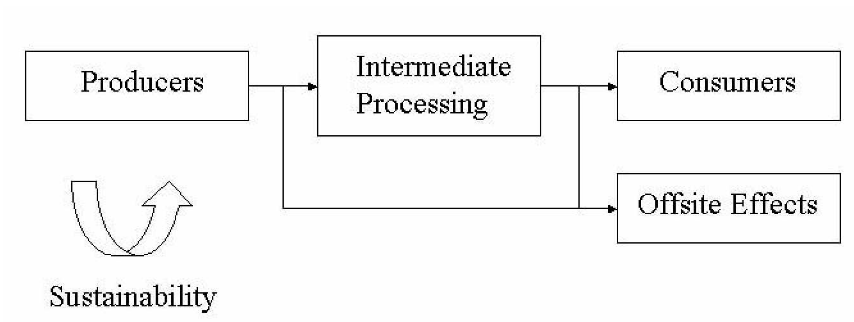

Fig. 12-1. A simple model of the agricultural system.

Even with the very simple model of cause and effect within an agricultural system in Fig. 12- 1, one can imagine roles for a number of DSS focused on producers. For example, producers interested in diversifying production could use a GIS tool to make the strategic decision of identifying new crops that could be grown in a particular microclimate. Operational and tactical decisions could be made with the International Consortium for Agricultural Systems Applications' Decision Support System for Agrotechnology Transfer, DSSAT (ICASA, 2004). The DSSAT is an internationally used DSS that allows researchers to model the response to management for many crops.

Other DSS that consider the interaction of producers, intermediate production, and consumers include the International Food Policy Research Institute's Dynamic Research Evaluation for Management, or DREAM program (IFPRI, 2003). DREAM is designed to evaluate the economic impacts of agricultural research and development, particularly innovations, such as new varieties of crops. Lastly, INIFAP's *Laboratorio Nacional de Modelaje y Sensores Remotos* (National Laboratory of Modeling and Remote Sensing) is working on a DSS to provide predictions of crop yields in their *Sistema de Predicción de Cosechas* (System of Crop Yield Prediction). This information, when combined with knowledge of existing stocks and demand from consumers, could provide crucial decision support on prices, imports, exports, and local supply problems to national-level policy makers in Mexico.

The rest of this chapter will focus on an example of a DSS to address natural resource management issues, primarily sustainability and offsite effects at the watershed scale. For decades, the foundation of technical assistance for sustainability in agriculture has been the control of sheet and rill erosion on sloped areas of cultivated fields. The approach is conceptually straightforward. The Universal Soil Loss Equation (USLE) or the Revised Universal Soil Loss Equation (RUSLE) is used to estimate erosion on a hillslope (Wischmeier and Smith, 1978; Renard et al., 1997). The USLE and the RUSLE are empirical models of the form:

$$A = RKLSCP \qquad [1]$$

A is soil loss in tons per acre; *R* is a rainfall-runoff erosivity factor; *K* is a soil erodibility factor; *L* is a slope length factor; *S* is a slope steepness factor; *C* is a cover-management factor; and *P* is a support practice factor. Essentially, the model captures the driving processes that cause hillslope erosion within a simple single equation that can be easily communicated. With the USLE and an estimate for the maximum acceptable soil loss, known as a soil loss tolerance, or *T* factor, soil conservationists had a powerful tool for identifying fields that needed conservation practices, as well as the range of alternative farming practices that would lead to acceptable levels of erosion. Erosion at a rate less than *T*, by definition, should lead to sustainable levels of crop production, at least as far as soil quantity is concerned. To illustrate, annual soil loss on a field with a suspected soil erosion problem would be calculated for the current management system. If *T* were exceeded, the *RKLS* factors would be held constant, and smaller *C* and *P* factors corresponding to alternative management practices could be applied until annual erosion was less than *T*. Some practices, such as installing terraces, would affect the *LS* factors as well. As soil conservationists gained experience under local conditions with the USLE, it became the standard tool, in part because of the ease with which it could be explained to farmers to support voluntary efforts to reduce erosion. Perhaps more important, however, was the overall simplicity of the approach, which was a conscious design decision. Laflen and Moldenhauer (2003, p. 39) relate discussions about the design of the USLE with Walt Wischmeier to that effect:

> It was clear from the writings that the scientists well understood the erosion processes, and the fact that these interactions were present. Walt indicated that the reason these were ignored in the USLE was that a technology was needed at the field level, and it could not be too complicated. It had to be delivered in manuals and field guides. If they had tried to incorporate these interaction effects (for example erodibility and climate), the technology would have been so complicated, using dozens of tables and charts, it would not have been used. It was this focus on providing technology for the user that made the USLE, and the group that developed it, so successful.

Although simple and powerful, the USLE is limited to predicting soil detachment but not transport and deposition. Soil eroded from an agricultural field could be deposited within concentrated flow areas or along the field boundaries. The USLE is not designed to address sediment delivery issues, though sediment delivery ratios or more sophisticated models can estimate the quantity of sediment entering watercourses. Nor does the USLE address the movement of nutrients and pesticides from farm fields to water bodies. Such issues require a field-scale simulation model. Nevertheless, RUSLE is still used today as the primary simulation model for conservation planning and implementation of government programs related to soil erosion. Moving beyond the USLE to consider other resource problems in addition to erosion will require a much more sophisticated approach capable of assessing many resource considerations.

The Conservation Technology Information Center (2005) has proposed more comprehensive, though still simple, approach to conservation. They promote the “Core 4” concept consisting of 1) conservation tillage, or tillage that leaves at least 30% residue cover at planting, 2) a crop nutrient management plan, 3) a comprehensive approach to weed and pest management that minimizes the application of agricultural chemicals, and 4) strips of permanent vegetation in sensitive areas in and around fields known as conservation buffers. Additional residue cover from conservation tillage coinciding with periods of high storm activity will reduce runoff, protect the soil surface, and increase organic matter near the surface. By reducing surface runoff and the concentration of pollutants in the runoff water, and with buffer strips to remove some of the remaining pollutants, there is a great potential to improve water quality.

In the United States, the Soil Conservation Service had long recognized that a producer should have a conservation plan that addresses management impacts on all resources. To emphasize the fact that the agency considered all natural resources, the agency changed its name in the early 1990s to the Natural Resources Conservation Service, or NRCS. At roughly the same time, the NRCS introduced a method known as the Conservation Practices Physical Effects, or CPPE, matrix (NRCS, 2003). The goal was to ensure that conservationists and producers looked broadly across all potential resource problems when formulating management systems.

The CPPE is used in the NRCS conservation planning process. During a resource inventory in the field, a conservationist will look for any of dozens of potential resource problems depending on the land use. These problems are grouped under the corresponding headings of Soil, Water, Air, Plant, Animal, and Human and are known collectively as SWAPA+H. Each potential resource problem has a quality criterion to indicate when it should be considered a problem. Once resource problems have been identified, management systems that resolve those problems are formulated.

Using observed data, simulation models, and expert opinion, one can prepare a table, such as Table 12-1, describing the effect of each alternative on a number of criteria of interest. Such a table could be simple or detailed depending on the decision makers' willingness to consider the complexities inherent in a given decision. Natural resource decisions typically involve tradeoffs, and a multiobjective approach is normally used if a table such as Table 12-1 can be created.

Table 12-1. The effect of management on decision criteria (to be quantified).

	Current Management System	Alternative 1	Alternative 2
1. Economic Returns	**?**	**?**	**?**
2. Sustainability			
Soil Erosion	**?**	**?**	**?**
Water Table	**?**	**?**	**?**
3. Offsite Effects			
Fertilizers	**?**	**?**	**?**
Pesticides	**?**	**?**	**?**

A number of multiobjective approaches have been proposed. The approach used in this research was first proposed by Wymore in 1988, adapted to natural resource decision-making in Lane et al. (1991), and implemented as the Water Quality Decision Support System, WQDSS (SWRC, 1994). An application of this method to water quality problems in agriculture is described in Heilman et al. (2004). The WQDSS has also been used for other applications, including shallow land burial systems for low-level nuclear waste (Paige et al., 1996), targeting farms for planning (Heilman et al., 1997), and rangeland planning (Lawrence et al., 1997). Imam (1994) addressed modeling and uncertainty issues.

The Queensland Department of Natural Resources and Mines, in association with the National Heritage Trust in Australia and under an International Memorandum of Understanding with the USDA-ARS, contracted with Netstorm, Inc. to implement the decision-making component of the WQDSS in the multi-platform Java language (Lawrence and Shaw, 2002). The new software is a generic, multiobjective decision-making tool called the Facilitator and incorporates the hierarchy tree of decision criteria by Yakowitz and Weltz (1998). This application pulls information from various sources to build the effects matrix that quantifies the impacts of the options on each decision criterion.

Because agricultural research institutions face similar challenges around the world, there is significant potential to address those challenges by developing DSS with shared or "open source" software that will allow for customization for particular needs while sharing much of the burden of writing the rest of the code for the project. Heilman et al. (2002) describe the open source effort to be used in further development of the Facilitator. The Java language source code can be accessed through the http://facilitator.sourceforge.net/ URL if modifications are needed.

Applications of the Facilitator have focused on planning for water infrastructure development in Queensland (Lawrence et al., 2000; Robinson et al, 1999), although the Facilitator has also been used to evaluate farming systems, floodplain management, farm forestry, animal production, project evaluation, and regional and watershed community strategy prioritizations. The Facilitator was designed for making strategic decisions where the problems are complicated enough to require a structured approach, and technical support is available to follow up on key issues affecting the decision. The three steps to make a decision using the Facilitator are 1) create a table of the effects of each alternative on each criterion by defining the decision variables or criteria, the management alternatives to be considered, and quantifying the effects of the alternatives on the criteria; 2) use available data, models, and expert opinion to score all values in the table to eliminate units and normalize elements to a scale of 0.0 to 1.0, with 1.0 being as good as possible; and 3) rank the decision variables in order of importance, graphically examine the results, and select the alternative(s) to implement or study in more depth. Lawrence et al. (2001) describe a richer conceptual framework of the many considerations and processes that lead to the definition of the alternatives and decision criteria within the decision analysis.

When performing the first step with the Facilitator, decision makers are responsible for excluding unacceptable alternatives. In the second step, decision makers select score functions for each decision variable from among the following choices: more is worse, more is better, a desirable range, or an undesirable range. The “more is worse” score function is used for a variable like the quantity of pollutants leaving a field or decline in groundwater levels, while net returns or grain yield are examples of decision variables that would be scored using a “more is better” score function. In some situations, surface runoff may constitute a “desirable range” where reducing the amount of runoff will reduce the transport of pollutants, yet some runoff is still desirable.

The third step assumes a simple additive value function of the form:

$$V(w,v) = \sum_i w_i v_i \qquad [2]$$

to calculate an overall value, *V*, as the sum of the products of a weight, *w*, associated with each decision variable, or criterion, *i*, and the score, *v*, for that decision variable. Although conceptually simple, the approach can be difficult to apply because decision makers find it difficult to assign weights. Yakowitz et al. (1993) developed a method that eliminates the need for decision makers to specify a weight for each decision variable. Instead, the decision makers rank the decision variables in order of importance, and software calculates the range of possible weighting combinations for the decision variables. This method calculates a range of values representing the alternative, rather than a scalar value that quantifies the overall value of the alternative.

The method developed by Yakowitz has an intuitive appeal to decision makers. Suppose there are n criteria, which the decision-maker has ranked in importance. Let V_{ij} be the score of alternative *j* evaluated with respect to criterion *i* in the importance order. If w_i indicates the unknown weight factor associated with criterion *i*, the highest (lowest) or best (worst) additive composite score for alternative *j*, consistent with the importance order, is found by solving the following linear program described for the weights w_i:

$$\begin{aligned} &max(min)\ V_j = \textstyle\sum_{i=1}^{n} w_i v_{ij} \\ &subject\ to\ \textstyle\sum_{i=1}^{n} w_i = 1 \\ &w_1 \ge w_2 \ge \ldots \ge w_n \ge 0. \end{aligned} \qquad [3]$$

In both cases (maximizing or minimizing), the first constraint normalizes the sum of the weights to 1, while the second requires that the solution be consistent with the importance order and restricts the weights to be nonnegative. The solution to the two programs yields the full range of possible composite scores given the importance order. Any weight vector consistent with the importance order will produce a composite score that falls between the best and worst composite scores. Yakowitz et al. (1993) also showed that the best and worst composite scores could be calculated in closed form, as the maximum or minimum composite score can be calculated by solving the following *k* problems, starting at the highest ranked criterion and adding criteria until they have all been considered:

$$v_{kj} = \frac{1}{k} \sum_{i=1}^{n} v_{ij} \qquad [4]$$

The best or worst composite score for alternative *j* is then selected from the results as:

$$BestScore = BV_j = \max_k \{v_{kj}\},$$
$$WorstScore = WV_j = \min_k \{v_{kj}\} \qquad [5]$$

A later study (Yakowitz and Weltz, 1998) improved the weighting algorithm by incorporating a hierarchical importance ordering, so that a number of sub-objectives could be grouped under categories, such as “erosion” and “water level” being grouped under “sustainability”. The hierarchy approach also addressed issues of bias caused by having too many criteria of one type (for example, environmental) compared to other considerations (for example, economic, social, cultural).

The multiobjective decision-making component is only a part of a DSS. Developing a DSS customized to a particular country’s institutions, customs, terminology and readily available data will probably require the development of additional software components. In recent years there has been significant progress in developing tools to manage the development of large-scale software projects. An impediment to the development of many software systems has been the inability of users to clearly articulate their needs. Users often do not have a good feel for what is possible, so while trying out prototype systems, they request changes that result in major design changes to support enhanced functionality. Such major design changes are costly and greatly slow the development effort, as developers are reluctant to revise systems in the face of frequently changing requirements. Many of the new tools are designed to support a more systematic definition of user requirements, allow for more meaningful interaction between users and the developer, provide additional flexibility in the design of software systems, and so ultimately speed the development of useful systems.

The first step in developing software is to define requirements. What will the software do? This is done iteratively. The best approach is to begin defining in general terms what the software will be designed to accomplish. Once that is done, another layer of specificity is added as many times as is needed to unambiguously describe the task that the computer code must accomplish.

One recently developed tool that speeds this process is the Unified Modeling Language (UML). UML should significantly increase the speed and flexibility of development by modeling the user interactions that software systems will have to support (Rumbaugh et al., 1999), including the concept of “use cases” to describe interaction with users (Armour and Miller, 2001). Leffingwell and Widrig (2000) also provide instructive advice on how to manage the overall process of defining software requirements. Clemens et al. (2003) describe an approach to documenting a software project that will support a flexible, modular approach. Once the software has been designed, a number of languages and development environments can make programmers more productive. One tool to support incremental development of software by large distributed teams of developers is the Concurrent Version System (CVS). Teams of programmers in different locations can work on small pieces of large projects, sharing and tracking each other's contributions.

Agricultural research institutions should implement DSS when the expected benefits are likely to exceed the costs. Obviously not all benefits and costs can be foreseen or quantified, but the issues that are good candidates for the development of a DSS are likely to share similar characteristics. Problems cannot be too complex. The problems must be salient enough to attract attention, but not so contentious that politicians feel compelled to resolve the issue without consideration of technical merits. A DSS is more likely to provide substantial benefits if economies of scale can be realized by applying the same system multiple times for different locations, or as part of an ongoing process over time. Lastly, a DSS is more likely to be used if only a few decision makers need to be trained.

DISCUSSION

Watersheds are a natural unit for managing surface water quality and quantity. Many natural processes are integrated across a watershed, and upstream impacts on downstream water users are obvious. Often forestry, grazing, or cropped agriculture is the most prevalent land use in the headwaters, and municipal and industrial uses for water dominate in the urban areas downstream. Because many people are involved, there is an obvious potential to provide significant net benefits if watershed management can be improved.

An example of a watershed needing a planning effort is Hydrologic Region 36 (Fig. 12- 2) in the States of Durango and Coahuila in north central Mexico. This 92,000 km^2 watershed drains the eastern side of the Sierra Madre Mountains into a large closed basin known as La Laguna. Precipitation ranges from 200 mm annually at the lower elevations to about 600 mm annually in the Sierras, with significant variability in all areas. The watershed characteristics and associated land uses can be divided into three regions: the upper section of the watershed on the flanks of the Sierras is very rough, primarily forested, with some grazing; the central section of the watershed is less steep and drier, primarily used for grazing; the lower section of the watershed is flat and takes advantage of the water in the Nazas and Aguanaval rivers for the cities of Torreon in Coahuila and Gomez Palacio and Ciudad Lerdo in Durango, as well an extensive area of irrigated agriculture.

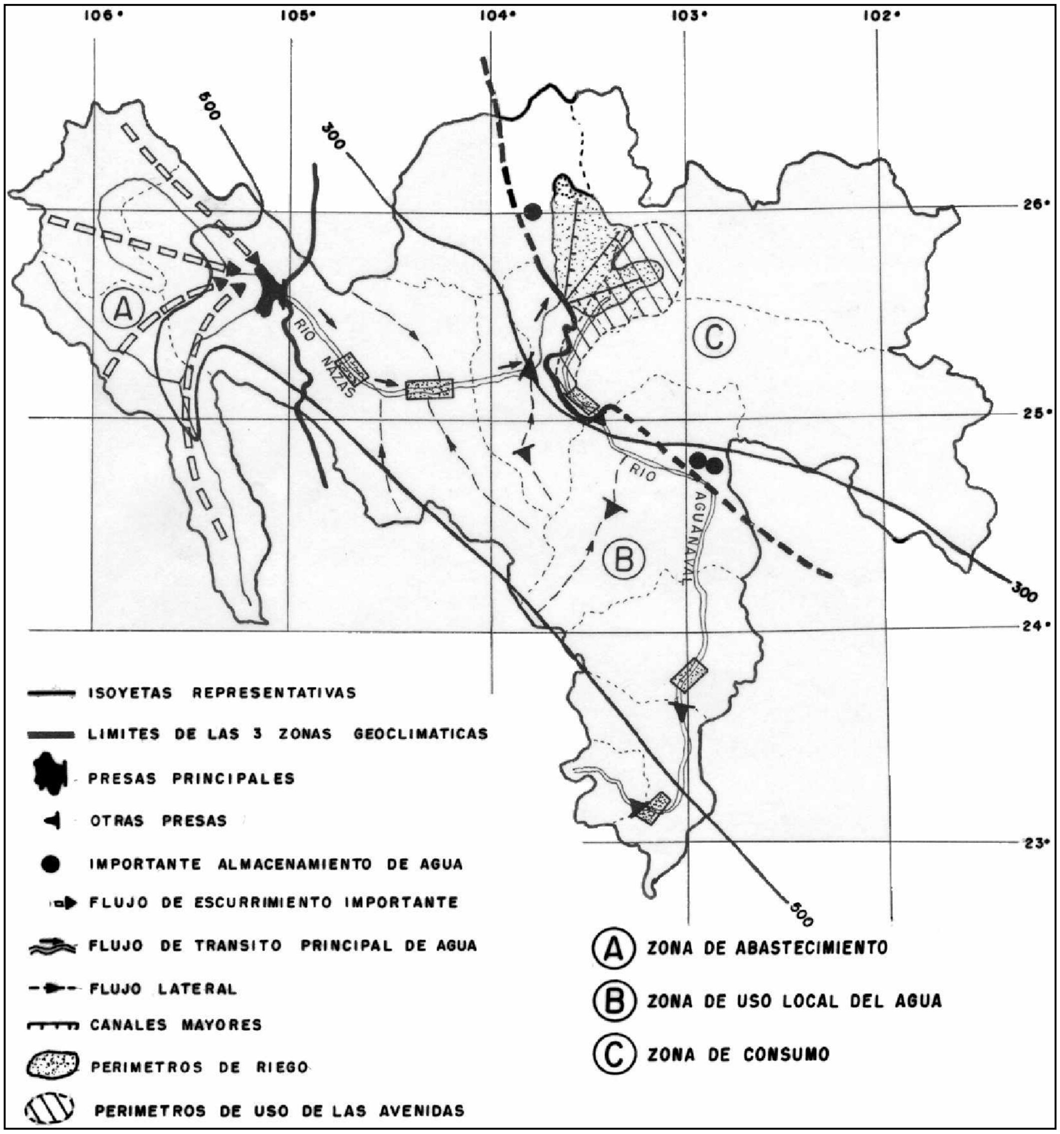

Fig. 12-2. Map of Hydrologic Region 36 showing the forested, water producing zone (A), the grazing, water for local use zone (B), and the irrigated, water consuming zone (C).

Field trips to inventory some of the common resource problems in the watershed were undertaken using a modified form of the SWAPA+H method for identifying resource problems. A one-page checklist of problems was developed for each of the three major regions and a rapid inventory performed. Table 12-2 shows the checklist for irrigated agricultural areas (in Spanish), and Table 12-3 summarizes the resource problems identified across the watershed (in English). The severity of the problems varied, but examples of most resource problems related to a particular land use could be found.

Table 12-2. Field checklist for irrigated agricultural resource problems.

Recurso	Consideración	Problema	Localidad	SI - Nota

SUELO	**Erosión**	**a. Laminar** **b. Eólica** **c. Flujo Concentrado** **d. Cárcavas** **e. Cárcavas temporales** **f. Inducida por riego**
	Condición	**a. Encostramiento** **b. Compactación**
AGUA	**Cantidad**	**a. Exceso de escurrimiento** **b. Salidas inadecuadas** **c. Uso ineficiente** **d. Azolve**
	Calidad	**a. Sedimentos** **b. Contaminación – pesticidas** **c. Contaminación – orgánicas** **d. Contaminación – patógenos** **e. Contaminación – nutrientes** **f. Salinidad** **g. Metales pesados** **h. Hábitat acuático**
AIRE	**Calidad**	**a. Particulas en suspensión**
PLANTAS	**Manejo**	**a. Manejo de nutrientes** **b. Maleza**
ANIMALES		
Fauna Silvestre	**Hábitat**	**a. Alimento** **b. Agua** **c. Protecciones**

A true watershed planning approach in Hydrologic Region 36 would include the effects of clearing upland forest vegetation on runoff volume and peak runoff rates in the rangeland and irrigated sections of the watershed. Grazing practices in the central portion of the watershed play a role in determining how quickly the Lázaro Cárdenas and Francisco Zarco reservoirs will fill with sediment. Lastly, the lower portion of the watershed is clearly influenced by the water quantity and quality coming from the upper portions of the watershed, and the urban areas in turn affect the upper portions of the watershed by consuming wood, livestock products, and through recreation.

Table 12-3. Identified resource concerns in the Río Nazas and Río Aguanaval watersheds of Hydrologic Region 36.

Resource†	Category	Specific Resource Concern‡	Irrigated Land	Rangeland	Forest Land
Soil	Erosion	Sheet and Rill		X	X
		Concentrated Flow		X	X
		Classic Gully		X	X
		Wind	X		
		Irrigation Induced	X		
	Condition	Soil Tilth	X		
		Compaction	X		

		Contaminants, Organic Wastes (P)	X		
Water	Quantity	Water Management	X	X	X
		Restricted Capacity, Lakes and Reservoirs		X	X
	Quality	Groundwater cont., Pesticides (P)	X		
		Groundwater cont., Nutrients and organics (P)	X		
		Groundwater cont., Salinity (P)	X		
		Groundwater cont., Pathogens (P)	X		
Air	Quality	Airborne Sediments	X		
Plants	Condition	Ecological Condition (productivity)		X	X
		Health and Vigor		X	
Animal Wildlife†	Habitat	Food	X	X	X
		Cover and Shelter	X	X	X
Animal Livestock	Habitat	Food		X	X
		Water, quantity and quality		X	X
	Management	Population/Resource Balance		X	X
		Animal Health (P)		X	

† Specific wildlife species not defined.
‡(P), Potential problem identified; cont., contamination.

For simplicity, this example focuses on the decision-making of the irrigated portion of the lower region. A further simplification is to only consider surface water. Groundwater is commonly used in this irrigated area, although the quantities and distribution of pumping are not well understood. Few irrigation pumps are metered, and groundwater and surface water are regulated by different sets of laws. Efforts have been made to quantify groundwater use through methods like remote sensing and estimating the quantities of water pumped through the electricity bills, but most producers are not forthcoming about groundwater use, so the situation is unclear, although estimates indicate that withdrawals may significantly exceed recharge.

This irrigation district is officially called the Comarca Lagunera or Distrito de Riego 017, (Fig. 12-3). The basis of this example is a report on the consolidation and development of District 017 by the Comisión Nacional del Agua (2003). DR 017 consists of 20 Civil User’s Associations, 17 of which are along the Río Nazas and 3 along the Río Aguanaval. There are 224,000 ha in the district, of which 93,000 are irrigated. The district consists of almost 38,000 members; 85% of the members belong to the collective landholding organizations, or ejidos, with the remainder considered small landholders.

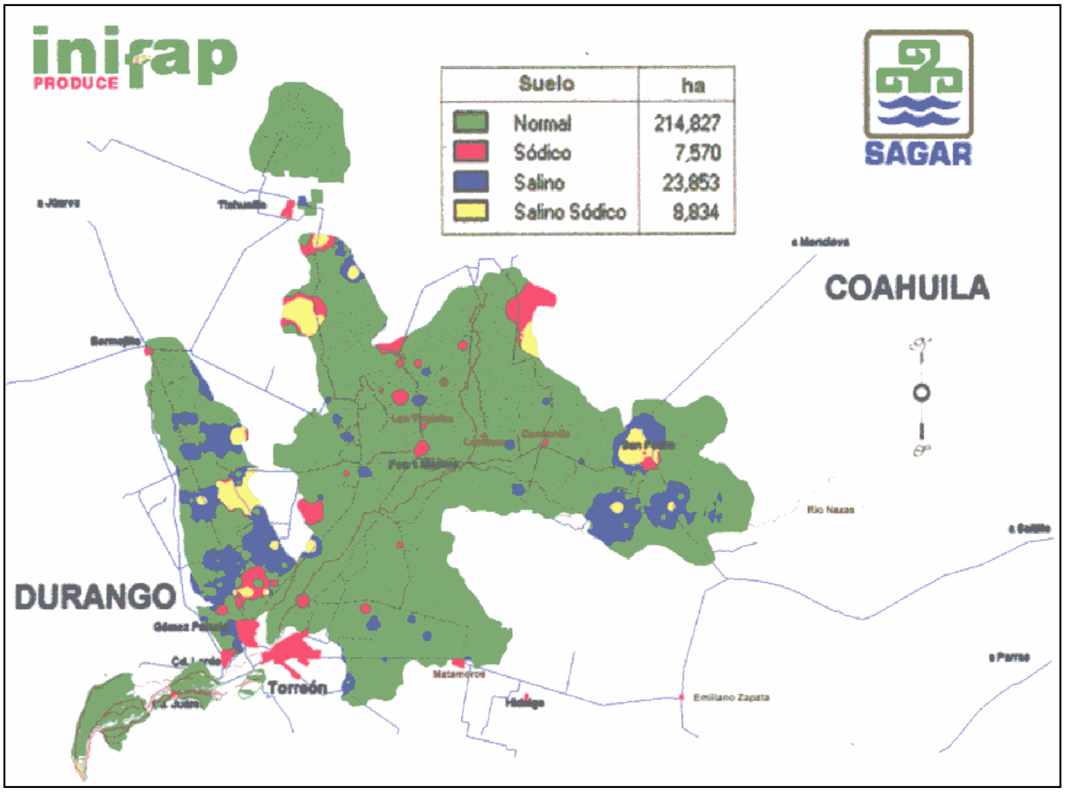

Fig. 12-3. Map of Irrigation District 017 showing the normal, sodic, saline and sodic and saline areas in the district.

Almost 2500 km of canals are used to distribute an authorized annual water volume of just over a million cubic meters. The quality of the water used is classified as poco contaminado, or slightly contaminated, in Mexico’s national water quality index, and is fit for human consumption.

Based on the quantity of water stored in the two dams on October 1 each year, legal constraints, and minimum requirements for conservation and ecology, the quantity of water to be released is determined and divided among the User’s Associations. Farmers then decide which crops to plant based on their allocation of water. The main crops are cotton, vegetables, and forages. Because of the varying supply of water and fluctuating prices, the area planted with each crop varies significantly each year. One trend has been toward increasing forage production, especially alfalfa, for the production of milk, as the region has developed into a major milk supply center. On the other hand, the area planted in cotton, corn, and beans has declined due to lower relative prices, although cotton prices and planned acreage may now be rising.

From the point of view of individual agricultural producers, the major problem is that water is available only to irrigate a few hectares, which is not large enough to provide a good income. Consequently, many producers are leaving agriculture. The government has a subsidy program to help producers called PROCAMPO. There has been a trend of smaller producers selling their rights to a year’s allocation of water to larger producers, with or without the PROCAMPO subsidy. Such sales raise long-term concerns about inequality in water use.

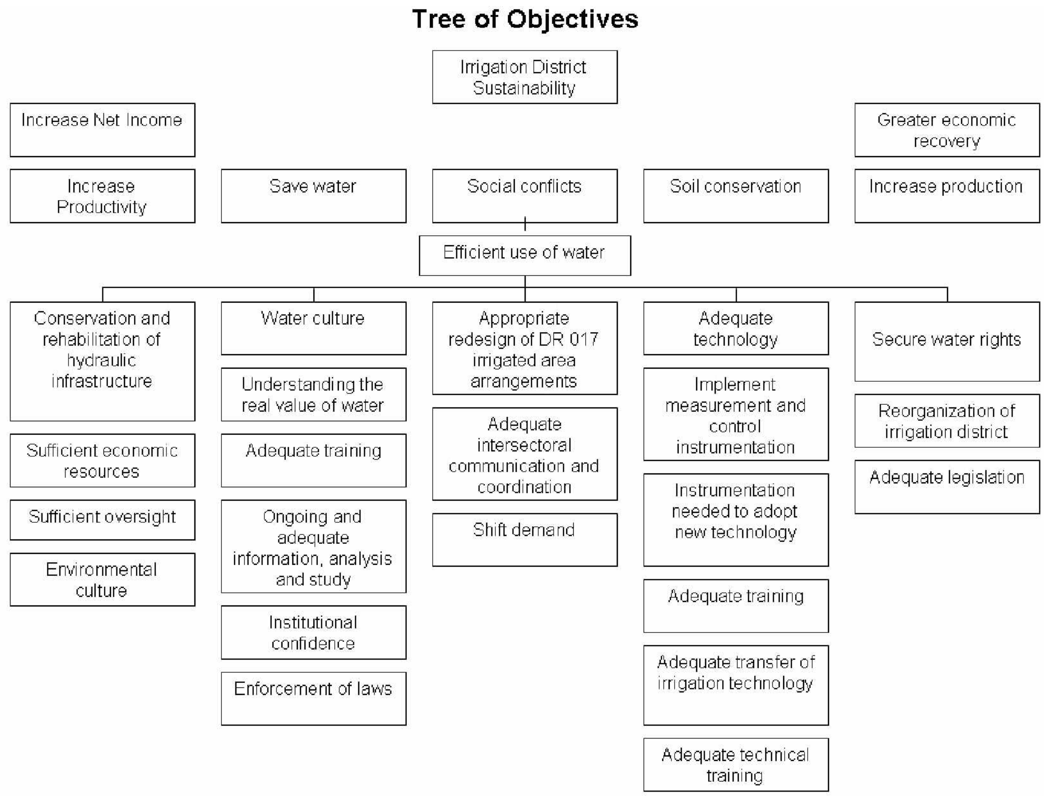

Fig. 12-4. Objective tree for Irrigation District 017.

From the point of view of the Irrigation District, there is a substantial problem with the efficiency of the system delivering water from the dams to the irrigated areas. Estimates of efficiency indicate that 63% of the water is lost between the dams and application on irrigated fields. Part of the problem is that, as there is not enough water to irrigate the whole district, water must be transported long distances to individual irrigated fields, rather than short distances to compact areas that are completely irrigated. A further complicating factor is the shift in responsibility for managing the canal network from the central government to the user groups. This shift has exacerbated planning and maintenance problems for the network of canals.

Finally, from the point of view of municipal and industrial water users, there is growing concern that agriculture uses a lot of water, but does not contribute economically in proportion to the amount of water consumed. If there is a shortage of water, the cities are entitled to use water first. Urban water planners realize that unless agriculture becomes more water-efficient, water may soon be less available and costlier for urban areas.

Given this background, the *Comisión Nacional del Agua* (C.N.A.), or National Water Commission, organized a study to determine what should be done to improve the management of DR 017. Specialists from a number of different agencies were brought together to define and document the problem. After creating a tree that identified a number of problems, a similar tree that defined objectives corresponding to each problem was created, as is shown in Fig. 12-4. For example, "Low Net Income" is identified as a problem (CNA 2003, p. 35). The corresponding objective is "Increase Net Income" (CNA 2003, p. 37). Figure 12-4 is a translation into English of the tree of objectives. The tree shows the overall goal is the sustainability of the irrigation district. This goal is divided into five objectives: increase net income, save water, avoid social conflicts, conserve soil, and increase economic recovery. The key objective of reducing social conflicts will require the efficient use of water. Because of the focus on water use efficiency, additional objectives contributing to that objective are also listed.

Representatives of the Ministry of Agriculture and DR 017 were invited to several decision support sessions using the Facilitator. A Spanish language interface to the Facilitator was created for these sessions. The representatives differed somewhat from the experts in the CNA study by wanting to focus on four objectives: increase the productivity of irrigation water, improve the distribution of wealth, increase the transportation efficiency, and increase the global efficiency of water in the irrigation system. In the context of the objectives shown in Fig. 12-4, these objectives focus on reducing social conflicts by solving the technical problem of the efficient use of water, and avoiding increased concentration of wealth.

The alternatives that the representatives of DR 017 considered also differed from the wider perspective in the CNA study. The DR 017 representatives focused on alternatives that were primarily under the control of the irrigation district, rather than specifying actions for the governmental water-related agencies. The alternatives considered include:

- Changing the cropping pattern to less water demanding crops
- Changing to winter forage crops to reduce evapotranspiration
- Training members of the irrigation district in water conserving technology
- Rehabilitating the hydraulic infrastructure
- Shrinking the irrigated area and introducing a water market
- Varying the price of water according to the amount in reservoirs
- Baseline – Continuing with current management

Using the understanding of the participants, Table 12-4 was created to show the English and Spanish names for the criteria and alternatives, and to describe the anticipated effect of each alternative on the objectives. Effects were estimated on a scale of 0.0 to 1.0, with 1.0 being as high as possible (maximum benefit / minimum impact). Since the estimates were directly generated as scores, there was no need to use a score function to eliminate units. If the baseline situation continued, the effect would be a score of 0.5 for each of the four alternatives. All other alternatives equaled or exceeded the baseline score of 0.5 for each objective. Often, when setting up a decision like this, there will be an economic objective, such as the cost to implement, for which alternatives with environmental benefits will have higher costs and thus lower scores than the baseline. Changing the cropping pattern, producing winter forage crops, and restructuring the district and implementing a water market all had positive effects for most objectives. The three alternatives deemed to have the greatest potential to achieve the stated goals were irrigation efficiency training, rehabilitation of hydraulic infrastructure, and varying the price of water.

Using the scores in Table 12-4, a number of importance orders ranking the four objectives were tried. These importance orders allow an opportunity for multiple stakeholders within the watershed to express their concerns or preferences for which decision criteria are most important to them. The Facilitator software allows these scenarios to be rapidly calculated and compared. In addition, the DSS tool calculates all possible combinations of weights that are consistent with the importance order of the criteria.

Table 12.-4 Irrigation District 017 estimates of management effects (scores) on objectives.

	Current Manage-ment System *(Situación Actual)*	Change Cropping Pattern *(Cambio Patrón de Cultivos)*	Produce Winter Forage Crops *(Cambio a Cultivos de Invierno)*	Irrigation Efficiency Training *(Capacita-ción a Usuarios del Riego)*	Rehabilitate Hydraulic Infrastruc-ture (Rehabilita-ción *de Infraestruc-tura Hidráulica)*	Water Market and District Restructu-ring *(Compac-tación y Mercado de Agua)*	Vary Water Price *(Precio del Recurso)*
Productivity of Water (*Productivi-dad del Agua de Riego*)	**.5**	**.7**	**.75**	**.8**	**.85**	**.7**	**.88**
Income Distribution	**.5**	**.6**	**.5**	**.5**	**.6**	**.75**	**.7**

(*Mayor distribución de la Riqueza*)							
Conduction Efficiency (*Incremento en la Eficiencia en Conduc-ción*)	**.5**	**.5**	**.6**	**.6**	**.88**	**.6**	**.8**
Global Efficiency (*Incremento en la Eficiencia Global*)	**.5**	**.7**	**.8**	**.87**	**.8**	**.6**	**.87**

The results of composite scores (weights * effects scores) are shown as a horizontal bar, where the minimum composite score defines the left side of the bar, and the right side of the bar is defined by the maximum composite score. Figure 12-5 shows one importance order selected, with the resulting outcomes shown as a graphic in Fig. 12-6. In this example, increasing the global efficiency of water used for irrigation was the highest ranked objective, so the two alternatives that scored 0.87 for that objective, irrigation efficiency training and varying the water price, were the preferred alternatives. The horizontal bar representing the range of possible overall scores for varying the water price (Precio del recurso) is much narrower than the horizontal bar for training water users (Capacitacíon a usuarios del riego) because the minimum score for the income distribution goal with the varying the water price alternative was 0.7, but only 0.5 for the training alternative.

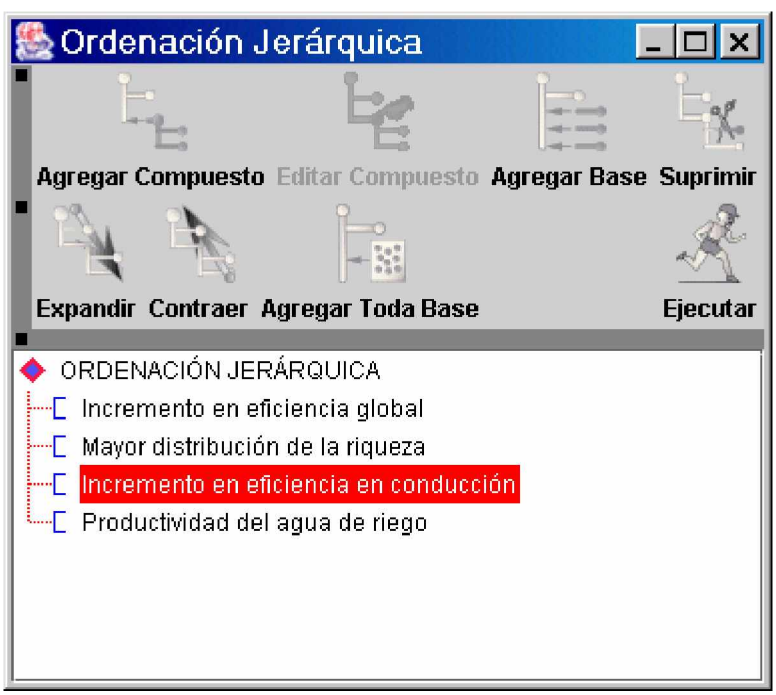

Fig. 12-5. Importance order (hierarchical ordering) within the Facilitator's Spanish language interface.

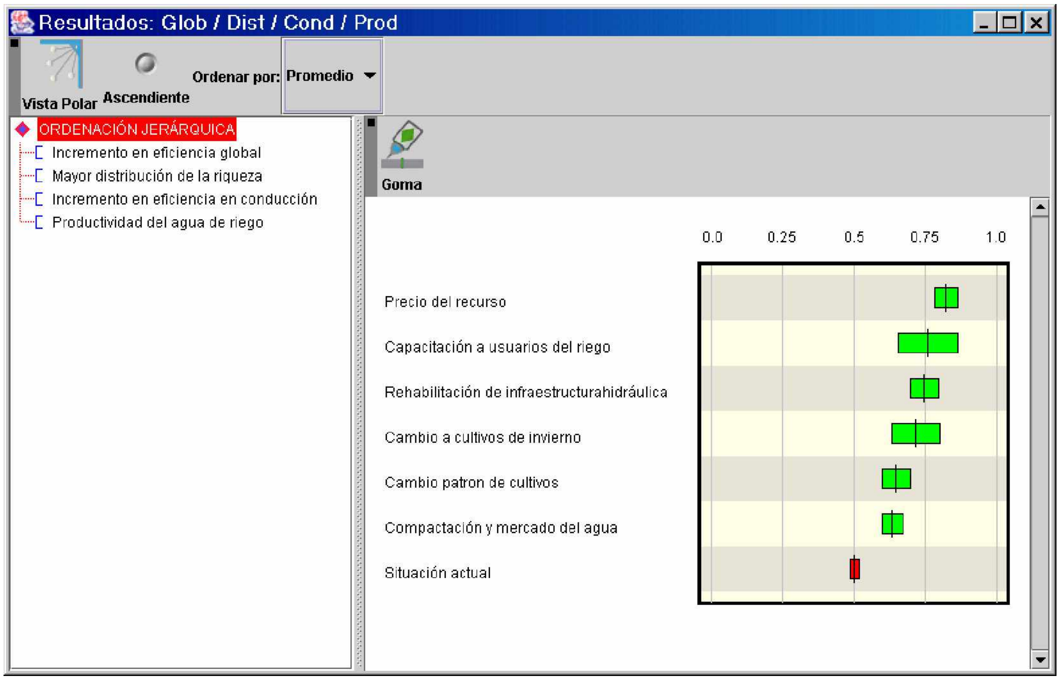

Fig. 12-6. Ranking of alternatives within the Facilitator's Spanish language interface.

Given the objectives, alternatives, estimated effects in Table 12-4, and several importance orders defined by the representatives of the irrigation district, the alternatives that tended to score the highest were varying the price of water and rehabilitating the hydraulic infrastructure. The alternatives that did the worst of those considered, though still scoring higher than the baseline situation, were changing the cropping pattern and shrinking the irrigated area and introducing a water market.

The irrigation district has not made a final decision on which alternative to implement. The application of the DSS is still an ongoing process, and there is an effort underway to improve the estimates of the effects of the alternatives on the objectives. The ALMANAC simulation model will be used to assess water savings resulting from a change to winter cropping. Economic studies to assess the response to varying the price of water and the feasibility of rehabilitating the infrastructure are also underway. A linear programming study has already shown that changing the cropping pattern could almost double income per cubic meter of water used and still save millions of cubic meters of water per year (Sanchez Cohen et al., 2003). Perhaps most encouraging has been the informal discussion with some of the other groups in Hydrologic Region 36 and their expressed willingness to work within the political system to help find additional funding to quantify decision variables.

To summarize the DR 017 example, watersheds are one area where a multiobjective DSS can make a contribution because of the need to integrate information from many sources. A DSS can frame a decision in a way that leads to the definition of critically important research questions. Generally, decisions involving natural resources are complex, and making decisions on one issue (e.g., economic) in isolation from other important considerations (social, environmental, institutional) may lead to decisions that are inconsistent with the principles of ecologically sustainable development. Whatever natural system must be managed will probably require an assessment of current condition that can benefit from remote sensing, as well as an understanding of how the components of the system interact, which can be provided through the application of simulation models. Ultimately, however, one would like to link all available information, such as natural resource inventories, simulation model results, and expert opinion, to both make decisions and guide future research.

CONCLUSIONS

Economic pressures, especially the rising cost of salaries for agricultural researchers, will continue to force agricultural research institutions to reassess their objectives. In the long run, successful responses to these economic pressures are likely to include efforts to help both the agricultural research institution and the agricultural sector as a whole to “work smarter”. Working smarter implies providing more and better information in a way that leads to better decisions.

Because there is a significant economy of scale in applying DSS technology, the decisions that are likely to be supported initially will be those relating to either policy or the management of large areas. To design a DSS, one has to determine who the decision-makers are, what decisions are to be made, and what information is needed to make those decisions. One can then identify the information to be collected by remote sensing and appropriate field inventory procedures. There are few areas in the world where adequate information at the landscape scale exists to support informed decision-making. Consequently, there will have to be an effort to understand and describe the physical factors across the landscape. Based on the demand for specific information, simulation models are chosen because of their ability to describe physical or biological systems and quantify the effects of management on key system outputs. Easy-to-use interfaces, data and time requirements can also be key determinants of which model to use. DSS complement remote sensing and simulation modeling by identifying the critical application areas needing focus.

Developing DSS technology is not a panacea and there are risks in implementing decision support technology. A very real risk is the possibility of outright failure. After investing in the development of a DSS, it may turn out that an unforeseen design flaw, a change in agricultural markets, lack of interest, political change, or some other factor prevents the DSS from being applied. In a case like that, the time and resources devoted to the DSS could have been put to a better use, particularly if the research institution has had to hire new personnel with information technology skills. Another potential source of failure is that even with user involvement in the decision-making process, implementing decisions may be problematic if significant institutional change is required.

The falling cost of hardware and the development of improved approaches to design and implement software systems imply that the real question is when, not whether, DSS technology will play a significant role in Mexican agriculture. Focusing initially on applications that other agricultural research institutions have already developed can reduce the risk of failure. The District 017 example showed the potential benefit of cooperating on an international effort that required implementing a Spanish language DSS interface, but not the full cost of developing the software. Not only is the cost of developing and implementing a DSS substantially reduced if other agricultural research institutions are working on similar tools, but experiences gained from previous applications can be shared. Other agricultural research institutions face similar economic pressure and thus have an interest in cooperating in the development of DSS products. Currently, a limited number of such cooperatively developed tools exist, although the number is likely to grow.

The DR 017 example also shows how a DSS, particularly a multiobjective DSS, could help coordinate disciplinary research that links agronomic, hydrologic and economic specialties. Perhaps the most significant contribution of a DSS to an agricultural research institution is to help it “fish” those projects of most immediate application out of the sea of potential research projects. A critical additional benefit is the realization by client groups that those key research gaps exist. Such groups may be willing to fund smaller scale research projects or work within the political system to find funding for larger projects.

Decision support technology can also help the agricultural sector as a whole work smarter. From society’s point of view, a basic question is how much money should be allocated to agricultural research. An economist would respond that the appropriate investment is the amount that maximizes the net returns. Of course, assessing returns to agricultural research is problematic. Benefits are uncertain and may be realized far in the future, prices are highly variable, etc. At some initial (low) level of investment, the overhead of running an agricultural research institution exceeds the return from research, and the institution fails to generate positive net benefits. At higher levels of investment, benefits of additional research activities exceed the combined overhead and research costs to provide positive net benefits. Funding should increase for activities with a greater potential until the net benefits equal those of other projects, and similarly, funding should decrease for projects without much potential. Finally, at some level of investment, there are no longer additional projects that provide the same returns, so net returns decline. In a watershed DSS application, some of the benefits would be realized as improvements in water quality and quantity rather than agricultural income.

This chapter has essentially argued that advances in information technology are creating the potential to create much greater net benefits from agricultural research. If an agricultural research institution can help the agricultural sector work smarter by considering more options, applying better science, focusing research on the most critical problems, and especially by realizing economies of scale in addressing common problems, then a greater investment in agricultural research is justified. To apply DSS technology will take careful thought and significant effort, but it can be a useful tool to help both agricultural research institutions, and the agricultural sectors they serve, to work smarter.

ACKNOWLEDGMENTS

We gratefully acknowledge the help of a number of researchers at INIFAP CENID RASPA, including Guillermo Martínez Rodriguez, Rodolfo Jasso Ibarra, and Ignacio Orona Castillo.

REFERENCES

Ahuja, L., L. Ma, and T. Howell. 2002. Agricultural system models in field research and technology transfer. Lewis Publishers, Boca Raton, FL.

American Water Resources Association. 2001. Proc. Conf. Decision Support Systems for Water Resources Management, Snowbird, Utah. 27-30 June 2001. AWRA, Middleburg, VA.

American Water Resources Association. 2002a. J. American Water Resources Association 38(2):337-586.

American Water Resources Association. 2002b. J. American Water Resources Association 38(4):895-1155.

Armour, F., and G. Miller. 2001. Advanced use case modeling. Addison-Wesley, NY.

Bakos, Y. 1998. Economics and technology: The productivity payoff of computers. Sci. 281(5373): 52.

Baumol, W.J., and A.S. Blinder. 1991. Economics: Principles and policy. 5th ed. Harcourt, Brace Jovanovich, NY.

Beinat, E., and P. Nijkamp (ed). 1998. Multicriteria analysis for land-use management. Kluwer Academic Publishers, Boston, MA.

Bonczek, R.H., C.W. Holsapple, and A. Whinston. 1976. Implementation of a decision support system for regional water quality processing. Paper 570. Krannert Graduate School of Management, Purdue University, West Lafayette, IN.

Bonczek, R.H., C.W. Holsapple, and A. Whinston. 1981. Foundations of decision support systems. Academic Press, NY.

Brooks, K.N., P.F. Ffolliott, H.M. Gregesen, and L.F. DeBano. 2003. Hydrology and the management of watersheds. Iowa State University Press, Ames, Iowa.

Clemens, P., F. Bachmann, L. Bass, D. Garlan, J. Iveers, R. Little, R. Nord, and J. Stafford. 2003. Documenting software architecture: Views and beyond. Addison-Wesley, NY.

Comisión Nacional del Agua. 2003. Consolidacion y desarrollo del Distrito de Riego 017, Comarca Lagunera. Comisión Nacional del Agua, Lerdo, Durango, Mexico.

Conservation Tillage Information Center CTIC. 2005 Core 4: Conservation for agriculture's future [Online]. Available at http://www.ctic.purdue.edu/Core4/Core4.html (accessed 14 June, 2005; verified 1 July 2005). CTIC, W. Lafeyette, IN.

Davenport, T.E. 2003. The watershed project management guide. Lewis Publishers, Boca Raton, FL.

De Steiguer, J.E., J. Duberstein, and V. Lopes. 2003. The analytic hierarchy process as a means for integrated watershed management. p. 736-740. *In* K.G. Renard et al. (ed.) Proc. First Interagency Conf. Res. in the Watersheds, Benson, AZ. 27-30 Oct. 2003. USDA-ARS, Tucson, AZ.

El-Swaify, S.A., and D.S. Yakowitz (ed.) 1998. Multiple objective decision-making for land, water, and environmental management: Proc. Int. Conf. Multiple Objective Decision Support Systems (MODSS) for Land, Water and Environmental Management, 1st, Honolulu, HI. 23-27 July 1995. Lewis Publishers, Boca Raton, FL.

Hammond, J.S., and R.L. Keeney. 1999. Smart choices: A practical guide to making better decisions. Harvard Business School Press, Boston, MA.

Heilman, P., G. Davis, P. Lawrence, J. L. Hatfield, and J. Huddleston. 2002. The Facilitator - An open source effort to support multiobjective decision-making. p.253-258. *In* Proc. Int. Environ. Modeling and Software Society, Lugano, Switzerland. 24-27 June 2002. University of Lugano, Lugano.

Heilman, P., J.L. Hatfield, M. Adkins, J. Porter, and R. Kurth. 2004. Field scale multiobjective decision-making: A case study from western Iowa. .J. American Water Resources Association 40(2):333:346.

Heilman, P., D.S. Yakowitz, and L.J. Lane. 1997. Targeting farms to improve water quality. Applied Mathematics and Computation 83:173-194.

Holsapple, C.W., and A.B. Whinston. 2001. Decision support systems: A knowledge-based approach. Thomson Learning/Delmar Publishers, Stamford, CT.

International Consortium for Agricultural Systems Applications. 2004. DSSAT: Decision support system for agrotechnology transfer [Online]. Available at http://www.icasa.net/dssat/ (accessed 14 June 2005; verified 1 July 2005). International Consortium for Agricultural Systems Applications, Honolulu, HI.

International Food Policy Research Institute. 2003. Dream: A tool for evaluating the effects of agricultural R & D [Online]. Available at http://www.ifpri.org/dream.htm (accessed 14 June 2004; verified 1 July 2005). International Food Policy Research Institute, Washington, DC.

Imam, B. 1994. Nonlinear uncertainty analysis of multiple criteria natural resource decision support systems. Ph.D. diss. University of Arizona, Tucson.

Janssen, R., and M. van Herwijnen. 1994. Definite: A system to support decisions on a finite set of alternatives. Kluwer Academic Publishers, Dordrecht, Netherlands.

Keen, P.G.W., and M.S. Morton. 1978. Decision support systems: An organizational perspective. Addison-Wesley, Reading, MA.

Keeney, R.L., and H. Raiffa. 1993. Decisions with multiple objectives: Preferences and value tradeoffs. Cambridge University Press, New York.

Laflen, J.M. and W.C. Moldenhauer. 2003. Pioneering soil erosion and prediction: The USLE story. World Assoc. of Soil and Water Conserv. Spec. Publ. 1. Funny Publishing, Bangkok, Thailand.

Lane, L.J., J.C. Ascough, and T. Hakonson. 1991. Multiobjective decision theory - Decision support systems with embedded simulation models. pp. 445-451. *In* Proc. Irrigation and Drainage, Honolulu, HI. 22-26 July 1991. ASCE, New York.

Lawrence, P.A., and J. Robinson (ed.) 2002. *In* Proc. Int. Conf. on Multiple Objective Decision Support Systems for Land, Water and Environmental Management (MODSS '99), 2nd, Brisbane, Australia. 1-6 July 1999. Report QNRM02143. Queensland Dep. of Natural Resources, QLD, Australia. Available at http://www.coastal.crc.org.au/modss/ conference99.asp (accessed 14 June 2005; verified 1 July 2005).

Lawrence, P.A., and R.J. Shaw. 2002. A framework for evaluating options for improved irrigation management. pp 1-15. *In* Proc. Int. Conf. on Multiple Objective Decision Support Systems for Land, Water and Environmental Management (MODSS'99), 2nd, Brisbane, QLD, Australia. 1-6 July 1999. Report QNRM02143. Queensland Dep. of Natural Resources, QLD, Australia. Available at http://www.coastal.crc.org.au/modss/conference99.asp. (accessed 14 June 2005; verified 1 July 2005).

Lawrence, P.A., J. Robinson, and R. Eisner. 2001. A decision environment: Going beyond a decision framework to improve the effectiveness of decision making in natural resource management. p. 1613-1618. *In* Ghassemi F. et al. (ed.) Int. Congr. Modeling and Simulation (MODSIM 2001), Canberra, ACT, Australia. 10-13 Dec. 2001. Modelling and Simulation Society of Australia and New Zealand, Perth.

Lawrence, P.A., R.J. Shaw, L.J. Lane, and R. Eisner. 2000. Participatory multiple objective decision making processes: Emerging approaches with new challenges. p. 1-11 *In* Marshall Flug et al.(ed) Proc. Watershed Management and Operations Management 2000, Fort Collins, CO. 20-24 June 2000. ASCE, New York.

Lawrence, P.A., J.J. Stone, P. Heilman, and L.J. Lane. 1997. Using measured data and expert opinion in a multiple objective decision support system for semiarid rangelands. Trans. ASAE 40:1589-1597.

Leffingwell, D., and D. Widrig. 2000. Managing software requirements: A unified approach. Addison Wesley, NY.

Loucks, D.P. 1995. Developing and implementing decision support systems: A critique and a challenge. Water Resources Bulletin 31:571-582.

Malczewski, J. 1999. GIS and multicriteria decision analysis. John Wiley and Sons, NY.

Marakas, G.M. 2003. Decision support systems in the 21st century. 2nd ed [Online] Available at http://myphlip.pearsoncmg.com/cw/mpbookhome.cfm?vbookid=403 (accessed June 14, 2005; verified 1 July 2005). Prentice Hall, Upper Saddle River, NJ.

March, J.G. 1994. A primer on decision making. Free Press, NY.

Matthews, R., and W. Stephens (ed.) 2002. Crop-soil simulation models: Applications in developing countries. CABI Publishing, NY.

McCown, R. L., Z. Hochman, and P. S. Carberry. 2002. Probing the enigma of the decision support system for farmers: Learning from experience and from theory. Agric. Syst. 74:1-10.

National Research Council. 1999. New strategies for America's watersheds. National Academy Press, Washington DC.

Natural Resources Conservation Service. 2003. Iowa’s Field Office Section V, Iowa eFOTG, National CPPEs [Online]. Available at http://www.nrcs.usda.gov/technical/efotg/ (accessed 24 Dec. 2003; verified 1 July 2005). USDA-NRCS, Washington, DC.

Newson, M. 1997. Land, water and development: Sustainable management of river basin systems. Routledge, NY.

Paige, G.B., J.J. Stone, L.J. Lane, D.S. Yakowitz, and T.E. Hakonson. 1996. Evaluation of a prototype decision support system for selecting trench cap designs. J. Environ. Qual. 25:127-135.

Power, D.J. 2003. A brief history of decision support systems. Version 2.8 [Online]. Available at http://DSSResources.COM/history/dsshistory.html (accessed 31 May 2003; verified 12 Jan. 2004).

Power, D.J. 2004. Decision support systems web tour. Version 4.3 [Online]. Available at http://dssresources.com (accessed 15 June 2002; verified 12 Jan. 2004).

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder. 1997. Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). USDA Agric. Handbook 703. U.S. Gov. Print. Office, Washington, DC.

Rizzoli, A.E. and A.J. Jakeman (ed.) 2002. Integrated assessment and decision support: Proc. Biennial Meeting Int. Environmental Modeling and Software Society, 1st, University of Lugano, Switzerland. 24-27 June 2002. University of Lugano, Lugano.

Robinson, J., P.A. Lawrence, R.J. Shaw, L. Cogle, K. Rose, and R. Lait. 1999. Development and outcomes from a multiple objective decision support system for the Cattle Creek Catchment. Dep. of Natural Resources, Mareeba, QLD, Australia.

Rumbaugh, J., I. Jacobson, and G. Booch. 1999. The unified modeling language reference manual. Addison-Wesley, NY.

Saaty, T.L. 1990. How to make a decision: The analytic hierarchy process. European Journal of Operational Res. 48: 9-26.

Sanchez Cohen, I., E. Catalan Valencia, M. Rivera Gonzalez, and M.A. Vuelvas Cisneros. 2003. Optimizacion del ingreso neto y productividad del agua en los Distritos del Riego del pais. CENID RASPA INIFAP. Ciudad Lerdo, Durango, Mexico.

Schmoldt, D.L., J. Kangas, G.A. Mendoza, and M. Pesonen. 2001. The analytic hierarchy process in natural resource and environmental decision making. Kluwer Academic Publishers, Boston, MA.

Shenk, T.M., and A.B. Franklin. 2001. Modeling in natural resources management: Development, interpretation, and applications. Island Press, Washington, DC.

Siegele, L. 2003. The IT industry. The Economist. 8 May. London, U.K.

Singh, V.P. 2001. Water Resources L.L.C. editor profile: Vijay Singh [Online]. Available at http://www.wrpllc.com/authors/singh.html (accessed 31 May 2003; verified 12 Jan. 2004). Water Resource Publications, Highlands Ranch, CO.

Southwest Watershed Research Center. 1994. A multiple objective decision support system for the USDA water quality initiative: Reference manual, version 1.1. USDA-ARS, Tucson, AZ.

Turban, E., and J.E. Aronson. 2000. Decision support systems and intelligent systems. 6th ed. Available online at http://cwx.prenhall.com/bookbind/pubbooks/turban2/ (accessed 14 June 2005; verified 1 July 2005). Prentice Hall, Upper Saddle River, NJ.

Walters, C. 1986. Adaptive management of renewable resources. The Blackburn Press, Caldwell, NJ.

Walters, C. 2001. Adaptive management of renewable resources. The Blackburn Press, Caldwell, NJ.

Wischmeier, W., and D. Smith. 1978. Predicting rainfall-erosion losses. USDA Agric. Handb. 537. USDA-Science and Education Administration, Washington, D.C.

Wymore, A.W. 1988. Structuring system design decisions. p. 704-709. *In* C. Weimin (ed.) Systems science and engineering. Proc. Int. Conf. on Systems Science and Engineering (ICSSE), Beijing, China. 25-28 July 1988. Int. Academic Publishers, Beijing, China.

Yakowitz, D.S., L.J. Lane, and F. Szidarovsky. 1993. Multi-attribute decision making: Dominance with respect to an importance order of attributes. Appl. Mathematics and Computation 54:167-181.

Yakowitz, D.S., and M. Weltz. 1998. An algorithm for computing multiple attribute additive value measurement ranges under a hierarchy of the criteria: Application to farm or rangeland management decisions. p. 163-177. *In* E. Beinat and P. Nijkamp (ed.) Multicriteria analysis for land use management. Kluwer Academic Publishers, Boston.