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ECONOMIC-ENVIRONMENTAL TRADEOFFS: METHODOLOGIES FOR ANALYSIS OF THE AGRICULTURAL PRODUCTION-RURAL ENVIRONMENT SYSTEM

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PREFACE

Undesirable environmental impacts of agricultural production are becoming more numerous as agricultural production is increased to meet world food demands. The question of environmental controls on agriculture has many implications on both the level of output from agriculture and upon the quality of the environment. The purposes of this paper are to 1) define a general structure for the agricultural production-rural environment system, 2) define a general analytical framework for management of the system, and 3) describe an empirical management study of water quality and erosion control.

I should like to add to the authors' preface a few words of my own. The following paper represents the contributions of a group of experts from the United States Department of Agriculture to the collaborative study with IIASA's task, "Environmental Problems of Agriculture." The study, culminating in this paper, met one of the Task's research objectives, which as stated in the Research Plan is, "an evaluation of the trade-offs between the intensification of agricultural production and the possible deterioration in environmental quality." The authors further present, in condensed form, an example demonstrating how a highly complex environmental problem can be analyzed. The methodology used for this analysis is not restricted to the study of agricultural-environmental interactions; rather, it can be applied on a wider basis.

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ECONOMIC-ENVIRONMENTAL TRADEOFFS: METHODOLOGIES FOR ANALYSIS OF THE AGRICULTURAL PRODUCTION-RURAL ENVIRONMENT SYSTEM

Adverse environmental impacts related to agricultural production include: groundwater pollution, fish kills due to pesticide applications, destruction of aquatic habitat from sedimentation, near extinction of some mammalian species due to land use changes, desertification due to overgrazing and many others. In fact, agriculture always leads to changes in the "natural" environment, if for no other reason, from the change in land from a "natural" condition to agricultural production. Although the problem has existed since the beginning of agriculture more concern is now being given the problem due to the great potential of current agricultural technology for serious environmental impacts and due to the increased environmental awareness worldwide.

In order to understand and manage the agricultural production-rural environment system it is first necessary to understand both how the components of the system interact and how the outputs of the system are related to human values.

A very simple structure of the rural environment-agricultural production system is displayed in Figure 1. Two aspects of this system are of critical importance. The first is the feedback link from agricultural production to the resource base system and to the ecosystem. Agricultural production thus impacts these other systems which in turn influence the future possibilities for agricultural production. The second is the linkage between both agricultural production, the ecosystem and the human values system. Just as food meets human needs and wants, so does environmental quality. It is obvious from such a system that tradeoffs exist between environmental quality and agricultural production. In addition, due to the dynamic nature of the feedback loops, tradeoffs exist both at the present and between the present and future. Since one of the outputs of the system is achievement of human goals, it is only reasonable to attempt to manage the system to obtain more rather than less achievement of human goals.

Many strategies and institutional arrangements exist for managing such a system. However, all the different institutions and strategies perform the same basic functions and process the same general types of information as displayed in Figure 2.

The key to the management system is that the control system is fed information on the achievement of human goals, labeled value indicators, and makes decisions which impact the physical-biological-social systems--labeled real systems. The real system is observed and measures of its state made--these measures are labeled technical indicators. The technical indicators are then translated by human perception and values into the value indicators.

If the transformation from technical indicators to value indicators is not made or not made properly, serious aberrations are introduced into the management system.

In the simplest case of this type of aberration, a single physical characteristic is identified and measured. No analysis of the relationship between human values and the physical characteristic is made. Either the assumption is made that the physical characteristic has values in and of

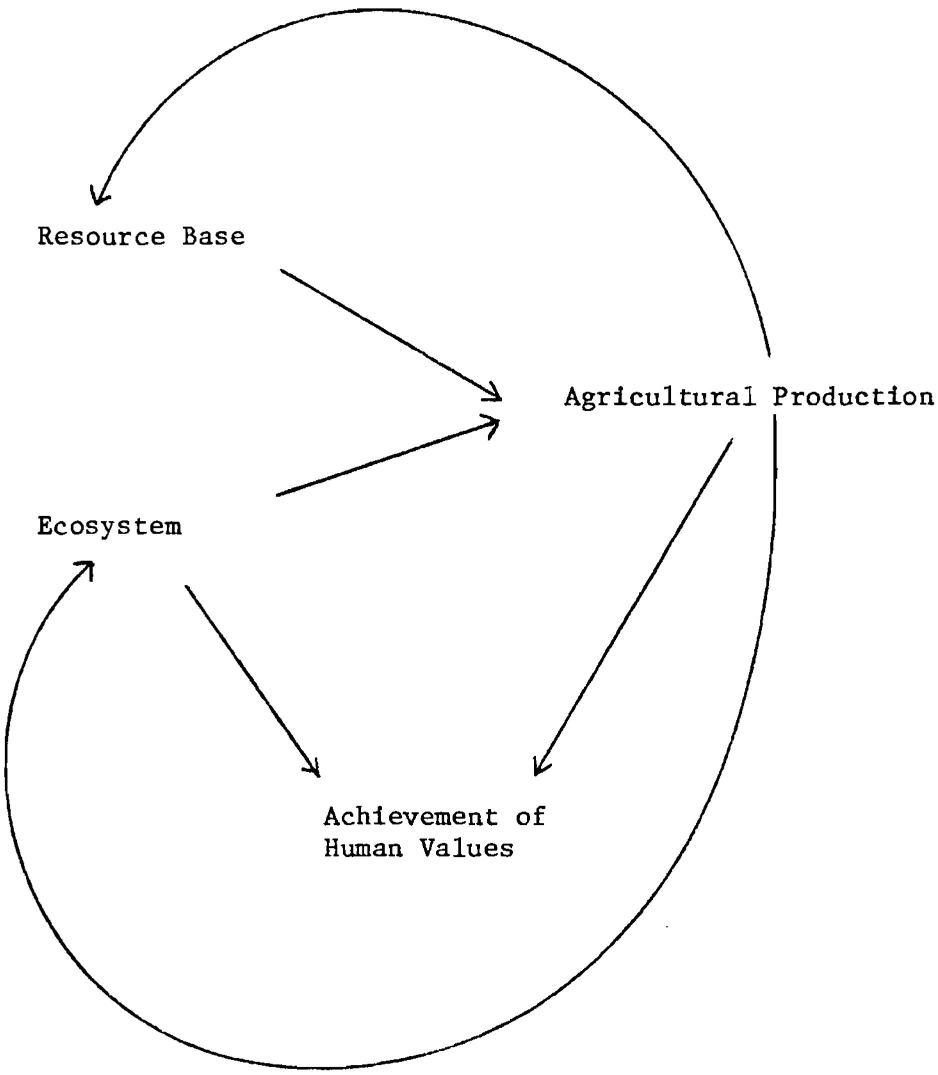

Figure 1. General System.

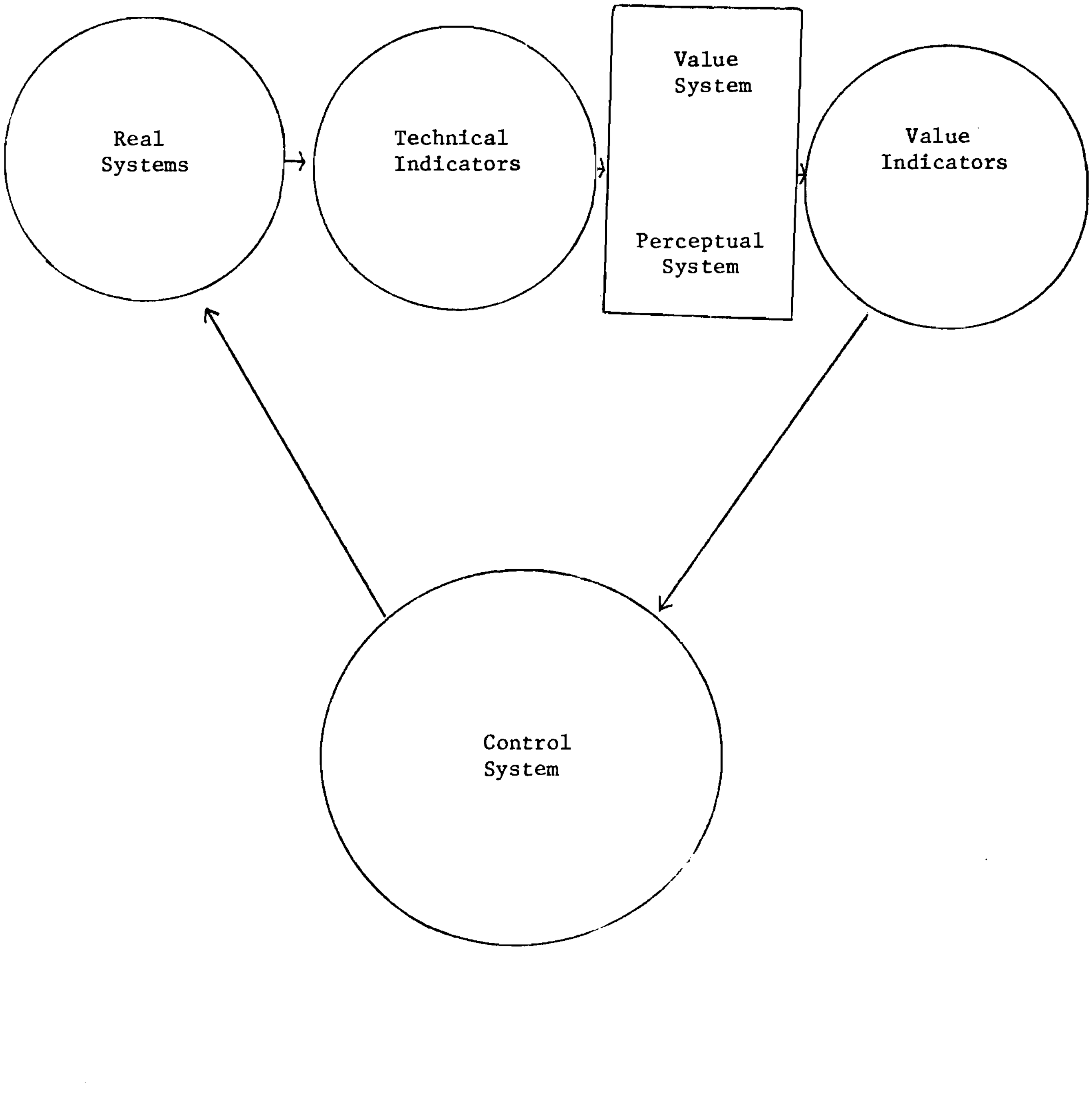

Figure 2. Management System.

itself or the assumption is made that however the physical characteristic is measured, this measurement is appropriate as a value indicator. This can lead to serious problems. For example, land subsidence in arid regions due to groundwater withdrawals is often mentioned as a critical problem of these areas. Statements such as "the land has subsided 10 meters" are made as if 10 meters were an indicator of human values. Unfortunately, there is almost no relationship between the distance the land surface sinks and human values. In one basin in Arizona, the land has sunk approximately 10 meters at the center of a basin which is about 50 km in diameter (McCauley and Gum, 1975). The impacts on humans consist of costs of maintenance of wells and a few thousand dollars a year to repair highway cracks. Yet land subsidence is often mentioned as a major reason for building the Central Arizona Project to import water at a cost of several billion dollars (Griffin, 1980).

Another example of the same aberration is the use of gross erosion as the appropriate measure of the environmental impact of erosion. In fact gross erosion is a very poor measure of the environmental impact of erosion and reducing gross erosion may have little effect on water quality oriented problems. Factors such as habitat types, particle size distribution of sediment, timing of erosion events, all must be considered in physically or biologically describing the environmental impacts of erosion. In addition the human values such as maintaining land productivity, aesthetics of streams, rivers, and lakes, and wildlife habitat values need to be explicitly considered in managing erosion. If such an approach is not used it is likely that resources will be spent to solve non-problems while the real problems with significant impacts on human values are ignored.

Many other cases exist where physical facts are used inappropriately. In fact, scientists are highly reluctant to use anything but "hard" physical facts for any purpose. That is fine for "science", but it is completely inappropriate to use physical measures as value indicators, and this being the case, methodologies are needed to incorporate directly the value and perceptual process into the planning process. The following is such a procedure (Figure 3).

Step one, of course, is simply to define the general problem and set limits on the problems to be studied. An example would be the water quality and erosion problem in the Willow Creek watershed in Oregon (USDA, 1977). From this general statement, the next step (2) is to define the aspects of human value (human goals) associated with the identified problem. Obviously, one set of values pertinent to such a situation is indicated by the products bought and sold in the marketplace. These values can be defined in traditional economic terms, using market observations of prices and quantities.

Other values exist and cannot be neglected. In fact, the whole area of environmental quality is not normally bought and sold in the marketplace and must be considered in other than economic measurements based upon market observation.

Two approaches are in general use. One possibility is to create a hypothetical market for environmental quality and measure values in monetary units. The second is to define and develop a value index for environmental quality in nonmonetary units (Gum, 1980). Both approaches are still in the evolutionary stage and there is no clear concensus at present as to which is best. For applications where cost benefit analysis is to be used as the planning and evaluation framework, the conversion of all values into monetary measures is appropriate and necessary. For applications where multiple objective planning procedures are to be used as the planning and evaluation framework, development of non-monetary indices is appropriate and necessary. It is the multiple objective planning approach (USWRC, 1973), which was chosen as the framework for this paper. Specifically two objectives are proposed (1) Economic Development, and (2) Environmental Quality. Traditional economic measures are proposed for the Economic Development account while an environmental quality index is proposed for the Environmental account.

The environmental quality index is of the form of a multiattribute utility function which serves the function of aggregating information on the many aspects of environmental quality into a single index.

One approach to define such a function is to construct a hierarchical goal tree with the general goal of environmental quality at the top and more specific subgoals as branches and subbranches of the tree. Figure 4 is an example of such a goal tree designed for the evaluation of a water quality and erosion control project (Willow Creek, Oregon). Further discussion of the construction of goal trees can be found in Gum, Roefs, Kimball, 1976.

Once the structure of the goal tree is established, it is necessary to select a function to aggregate the values from the most specific branches to the general goal and to estimate the parameters of this function. While many functional forms could be used, the form corresponding "best" to experimental results on the human perception and value process is a power function homogeneous of degree 1. The parameters of such a function are simply the exponents of the elements and can be referred to as preference weights. For example, the multiattribute utility function corresponding to the goal tree in Figure 4 is:

PROCESS

1. DEFINE PROBLEM.
2. DEFINE GOALS.
3. DEFINE TECHNICAL INDICATORS.
4. MODEL TECHNICAL TO GOAL CONNECTION.
5. DEFINE ALTERNATIVES.
6. MODEL ALTERNATIVE TO TECHNICAL INDICATOR RELATIONSHIP.
7. DEVELOP MANAGEMENT MODEL TO DISCOVER A REASONABLE SET OF ALTERNATIVES.
8. PRESENT RESULTS TO DECISION MAKERS.
9. REPEAT ABOVE AS USEFUL OR NECESSARY.

Figure 3. Planning Process.

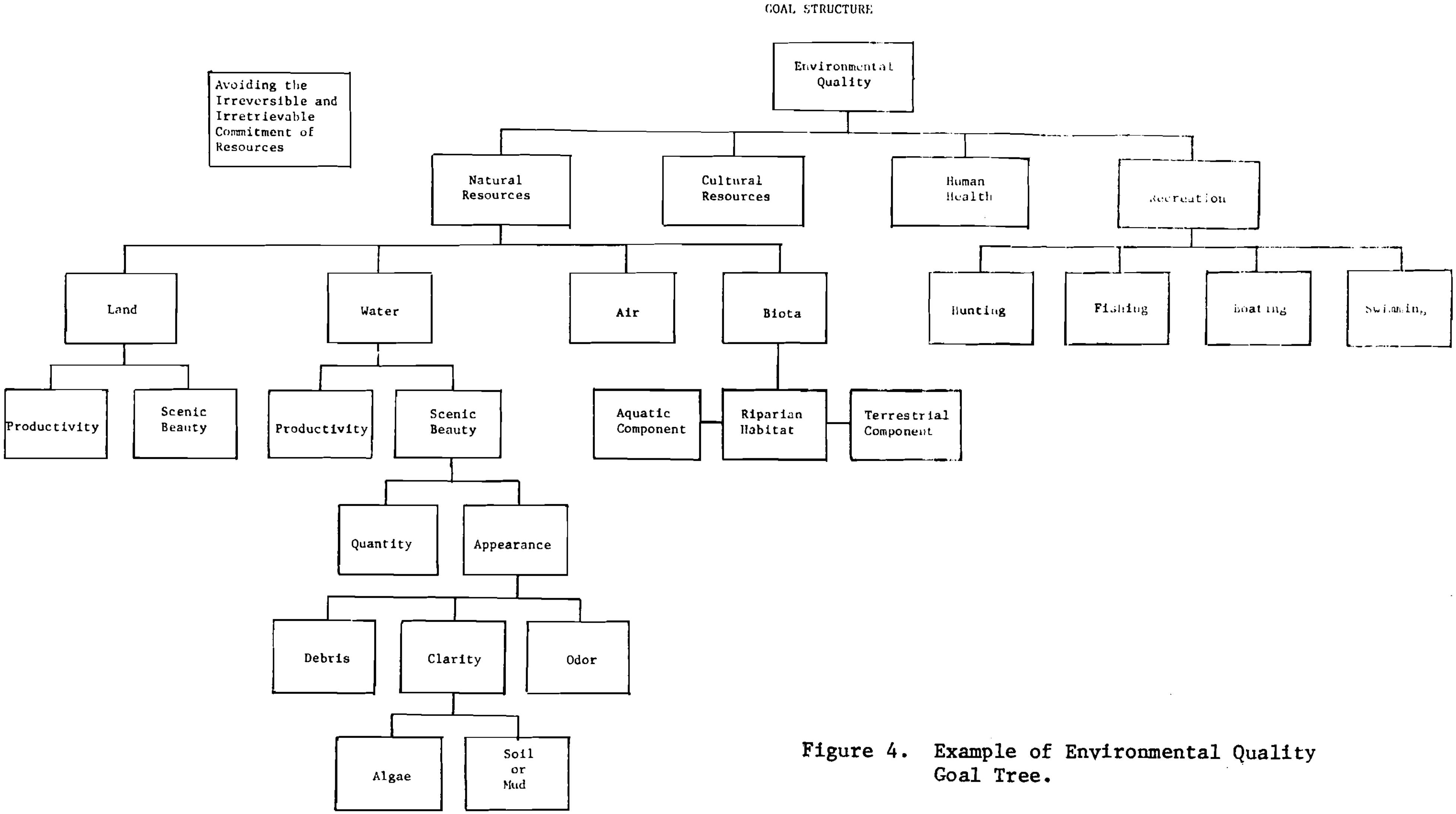

Figure 4. Example of Environmental Quality Goal Tree.

$$\text{E.Q. index} = \sum_{i=1}^{n} X_i^{w_i}$$

where X_i is the measure on a 0 to 100 scale of the level of attainment of goal i and w_i is the preference weight for goal i.

The preference weights can be generated by several different approaches. One reasonable approach is to use an opinion survey of the general public to develop these weights. A second approach is to use the opinions of the policy makers to determine weights. Discussion of the methodologies for obtaining the weights can be found in Gum, Roefs, and Kimball, 1976.

The next step (3) in the process is to define the technical indicators to be measured. Data availability, model availability, the specific characteristics of the problem, and research resource constraints will in part determine the choice of technical indicators.

For the example of erosion and water quality improvement a very large number of possible technical parameters exist. For example the U.S. Environmental Protection Agency has a data system which reports on over 2000 different physical and biological water quality parameters. The basic criteria for selecting among the large number of possible criteria are 1) is variation in the lowest level subgoals such as debris, odor (see figure 4) related to the technical indicator, and 2) so models exist to relate the variation in technical indicators to the alternatives to be studied.

A perfect study would select technical indicators and models which would accurately and completely relate all possible alternative plans to the human goals. Perfect studies do not, nor will they ever, exist. Tradeoffs exist between accuracy, completeness, analysis time, and analysis cost. In fact the selection of technical indicators, modeling approach and analytical technique is a decision involving multiple objectives. For the Willow Creek application the following technical indicators were selected.

Lowest Level Subgoal	Technical Indicator
Land Productivity	Years of topsoil remaining
Land Scenic Beauty	Composite index of land use-beauty value
Water Productivity	Water yield in acre feet per year
Water Scenic Beauty	
Quantity	Flow in cfs
Water Appearance	
Debris	Percent of water surface affected by debris
Odor	Summer water flow in cfs
Clarity	
Algae	Percent water affected by algae
Sediment	Suspended sediment in mg/1.
Air Quality	Number of Days particulate quality standards are exceeded
Cultural Resource Quality	Actual accounting of resources and effects
Health	Contaminated drinking water sources
Biota Quality	Index of riparian habitat quality (Oswald, 1980)

Recreation Quality	Water Scenic Beauty Index (composite index of quantity and quality consideration)
Fishing Quality	
Swimming Quality	
Boating Quality	
Hunting Quality	Terrestrial component (sub index) of riparian habitat index

These technical indicators were judged to measure almost all of the changes in the environmental quality goals (Figure 4). Additionally a set of models to relate these technical indicators to the plans were selected and will be discussed latter. These technical indicators provide basic information to allow the estimation of impacts and plan on the environmental quality goals is available.

After technical indicators have been chosen, they must be related to the value components of the goal tree (step 4). For example, if mg/l of sediment is chosen as the technical indicator for the measure of the soil component of water clarity, then a transformation of the physical units into value units must be found.

If we define the value scale as a 0 to 10 scale where 0 is the worst possible case and 10 is the best case, the problem becomes one of mapping ppm sediment onto the value scale. In quantifying this relationship, two major problems are encountered. First, value is subjectively perceived, not measured in the same way technical indicators are measured by a directly observable physical "yardstick." Secondly, although the general public perceives achievement of social goals (environmental goals), the technical phenomena that underlie their perceptions are usually understood only by specialists. The first problem can be reconciled by using surrogate measures, indices, for value or goal achievement. The second problem can be solved by collecting information on connective relationships from groups of people that have both perceptions of goal achievement (and knowledge of the perceptions of others) and knowledge of technical measures. These groups should consist of experts in the relevant aspects of environmental management. A multidisciplinary group is usually necessary due to the wide range of technical indicators impinging on environmental quality.

The decisions made by this group fall into two categories. They should:

1. Attempt to achieve consensus on the current value of a lower level subgoal, both in terms of the technical indicators and the surrogate index.

2. Establish the functional relationship between the technical indicator and value scale.

The Delphi method may be used as the mechanics of the group to develop the information necessary to define these connectives (Dalkey, 1969). Delphi is a vehicle to solicit and collate informed judgements about the present and future. The Delphi method provides rules for using expert judgements to find better answers to uncertain questions. If a simple perceptual experiment is done or Delphi procedure followed the result might be similar to Figure 5. At a concentration of 0 ppm, people will perceive the water to be perfect on the clarity index. As the concentration of sediment increases there will be decreases in the value index until approximately 2200 ppm of sediment is reached, after which point people are unable to perceive any further degradation in water clarity.

If our management system is a daily or instantaneous system, the above measure is appropriate; if, however, a management system is an annual system, then the problem of aggregating over time arises. Consider Figure 6.

THE GOAL IS WATER CLARITY.

THE TECHNICAL MEASURE IS

THE SEDIMENT CONCENTRATION.

CURRENT TECHNICAL LEVEL

CURRENT GOAL LEVEL

TECHNICAL TO GOAL FUNCTION

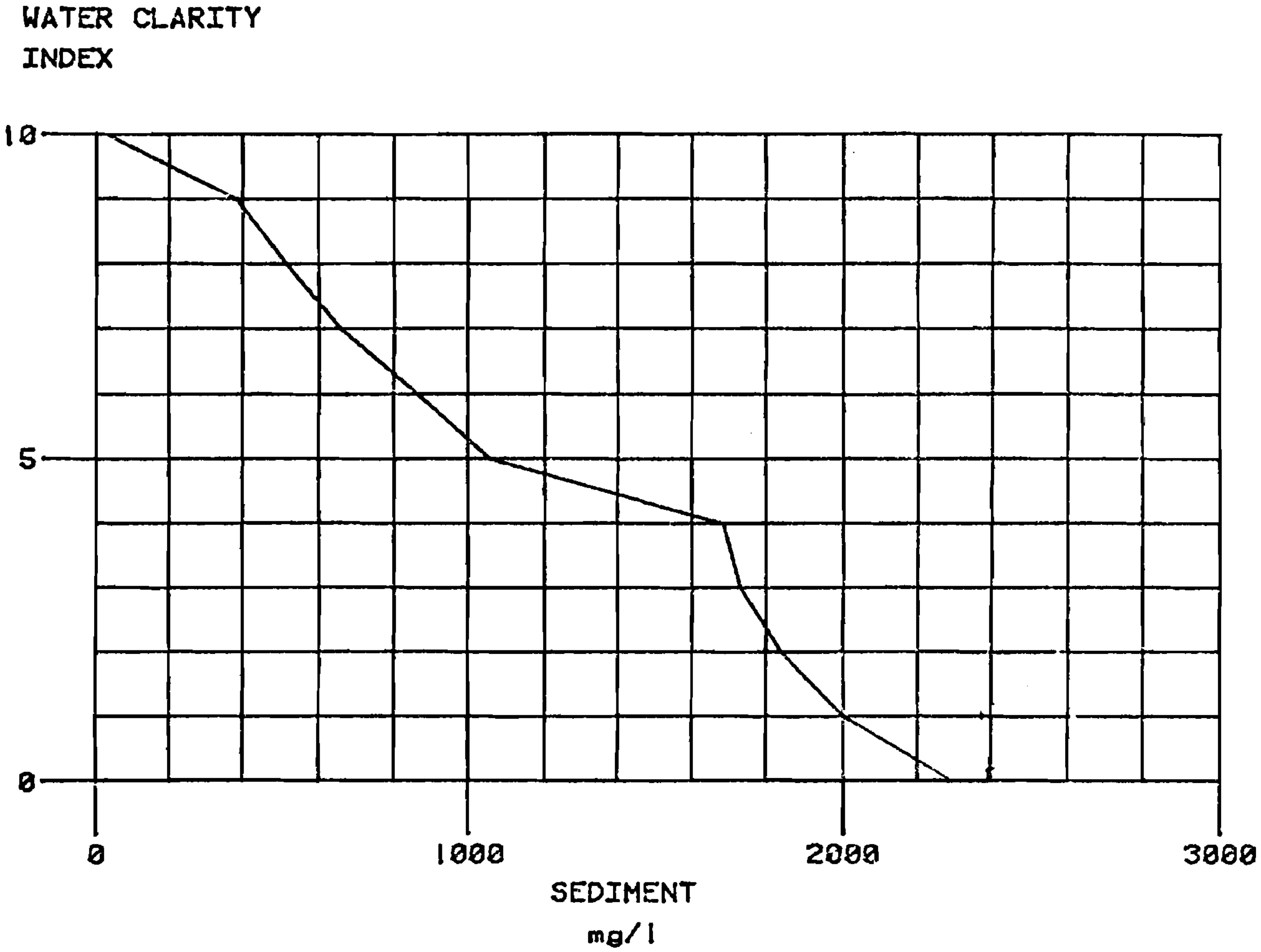

Figure 5. Physical to Value Link for Sediment to Water Clarity.

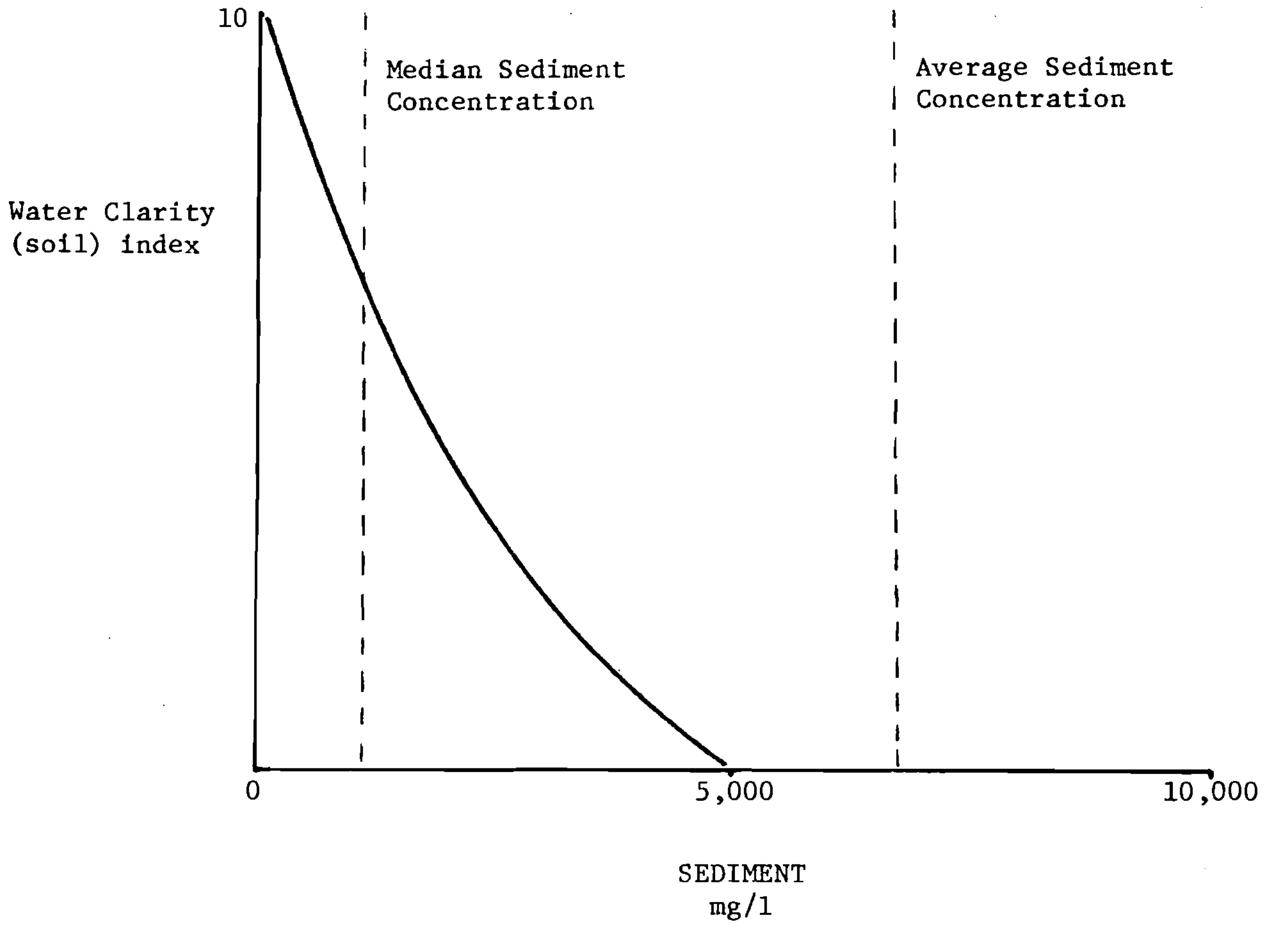

Figure 6. Example of timing problems in Goal Measurement.

Due to severe storm events causing extremely high levels of sediment to be carried off, the value of the goal, if the average sediment value is used, will be zero. However, the value of the goal, if the median sediment concentration is used, will be much higher and is a more logical representation of people's average value of the water clarity goal over the period of a year. The best method would be to calculate the value of the goal for each day of the year and average these values for a yearly measure of the goal.

The next step (5) in the process is to define the possible alternatives to be investigated. These might range from construction alternatives to economic incentives for implementing certain management practices to legal regulations and others. In the evaluation being conducted for the Willow Creek sub-basin in Oregon, alternatives will combine the structural practices of terracing, diversions, sediment ponds and grade stabilization with vegetative and management practices such as grassed waterways, reduced tillage, residue management and mulching, contour and strip cropping to achieve project goals of erosion and sediment reduction.

Once a set of alternatives is defined it is necessary to relate the alternatives to the technical measures (step 6). At this point, corresponding mathematical models must be used. If, for example, the alternatives include alternative land management techniques, then their impact on erosion, and sediment in waterways must be modeled. Just as in the selections of technical indicators, the selection of models will depend upon the specifics of the problem and the resources available for the research. The basic model selected was the Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1980). The model will allow the estimation of the timing and character, as well as amounts of chemical and sediment produced by agricultural production systems.

Additional models necessary include a habitat model to estimate the impact of alternatives. The basic form of the model is based on the Habitat Evaluation Procedures (HEP) of the U.S. Fish and Wildlife Service (revised 1978). A further discussion of the Riparian Habitat model can be found in Oswald 1980.

Further discussion of the Land Quality submodel can be found in the Impacts of Resource Management on Land Quality: A Structure for Analysis, a working paper in draft form at this time authored by Eric B. Oswald. Water resource quality and resource management practices is discussed in detail in Oswald, 1978.

Once the technical impacts of the alternatives have been modeled, they can be expressed in the goal values by use of the transformations developed in step 4 of the process. At this point, the necessary information for a mathematical programming model to select a reasonable set of alternatives to present to the decision maker has been developed (step 7). The general form of the programming model is to maximize the environmental quality goal subject to physical and economic restraints. Separable programming can be used to allow a linear programming algorithm to solve the maximization of the nonlinear objective function. This approach is defined in Stellern, Gum, Arthur, Oswald, 1979. By varying the level on the economic constraint, a tradeoff frontier between environmental quality and economics can be developed (Figure 7).

The results of this process can then be presented to decision makers for a final decision or for suggestions on revision and improvement.

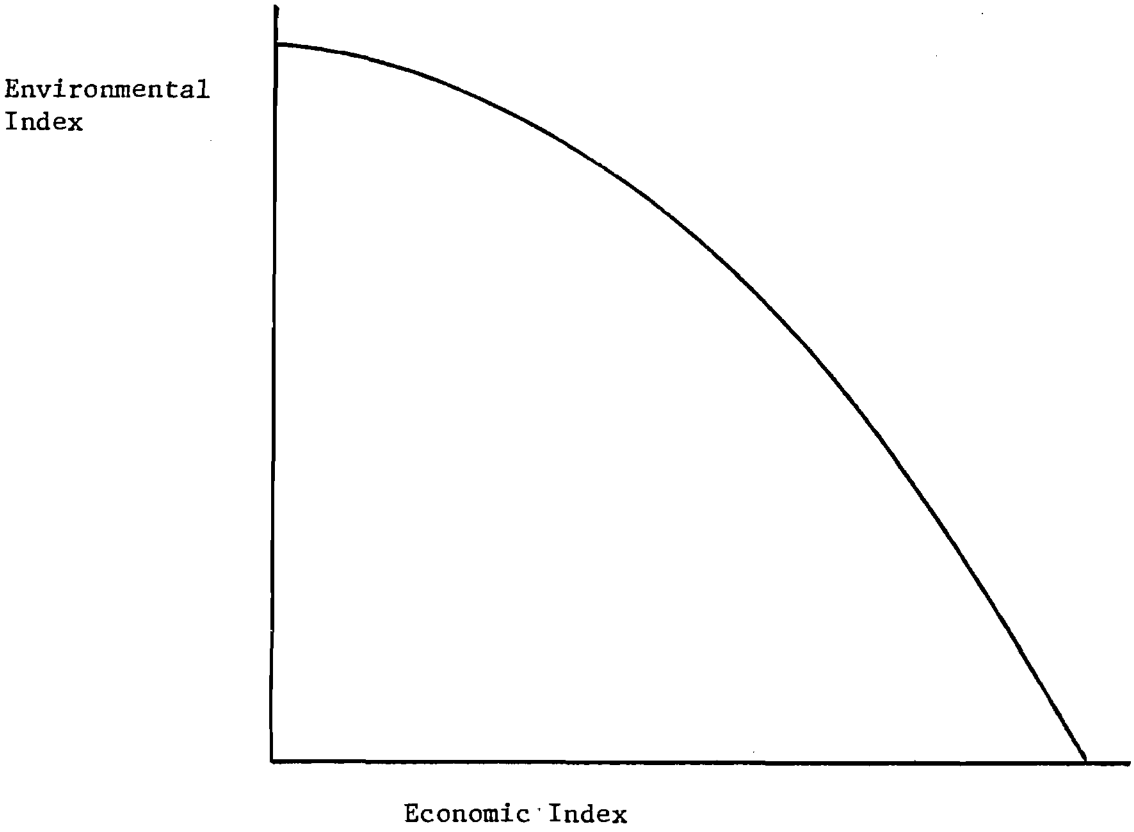

Figure 7. Trade-off Frontier

Summary

The above process is reasonable both in theory and in practice for the evaluation of rural environment vs. agricultural production problems. While it, in general, seems very complicated, it becomes much simpler for most applied problems. For example, in most applied problems alternatives may not impact a specific subgoal, for example, air quality. In this case, little attention needs to be paid to models of air quality or data on air quality and so on.

In addition to providing recommendations to decision makers, the process has the characteristic of forcing the analyst to think of the human dimensions of a problem, not just the technical aspects of a supposed problem. It may be that this characteristic of the methodology is of the most value.

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