LAND USE PLANNING WITH MULTIOBJECTIVE PROGRAMMING: A MODEL FOR FOREST DEVELOPMENT IN THE HILLS OF NEPAL

by

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(ABSTRACT)

A land use planning model was developed for long term planning of renewable natural resources development in the Hills of Nepal. Considerable emphasis was placed upon identifying land use planning problems for the prevalent limited market economy and subsistence farming system.

A multiobjective programming model was chosen for modeling the land use planning problem. The model accomodated five objectives: namely, increasing food, fodder and fuelwood production and decreasing soil loss and cost. A weighting technique within the multiobjective framework was developed to facilitate land use planning as a socio-political decision making process. The application of the model was demonstrated with data from Phewa-tal watershed.

The model generated technically efficient alternative land use plans. It also generated information on time flow of achievement levels of the objectives and their trade-offs in each alternative plan. Very few alternative plans were generated when the periodic growth rates on achievement levels of the objectives were tightly constrained. The model also provided information on periodic deficit and surplus achievements of the objectives. This information provided the guidelines for evaluating the plans.

The model provided a useful mathematical structure for analysing land use planning as an integrated planning process coordinating multi-sectoral objectives in time and space. A

foundation has been laid for constructing comprehensive land use planning models in subsistence farming economy in developing nations. The model was run on a commercially available software package and a portable personal computer. Therefore, the model can be applied in the field situation in many developing countries.

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Chapter I

INTRODUCTION

Several land use planning models have been developed applying mathematical programming techniques. As a result, modeling of policy and management problems of public land resources planning have been enhanced. Most research in land use planning models has been sectoral and assumes a well developed market economy. They have not fully addressed the specific characteristics of the problem and decision making environment of many developing countries.

This study was an attempt to develop a multiobjective land use planning model for the Nepalese Hill areas. Land use planning was addressed in the context of noncompatible objectives and limited market opportunities. The limited market economy is typical of subsistence farming prevalent in many developing countries. The model also contributes by developing an objective weighting technique within the multiobjective programming framework. The weighting technique facilitates land use planning as a socio-political process.

Rationale for land use planning

Land use planning is defined broadly in many ways to mean many things. Some definitions limit land use planning to public policies, rules and regulations that guide the use of lands not owned or controlled by government (Sampson, 1975 and Stine and Byrne, 1982). The end product is usually defined in such broad terms (for example, a high quality environment). Land management planning is defined as dealing with lands that an individual, corporation, or agency manages, controls or owns. Project planning is defined as construction of a project that involves land resources.

The planning model in this study views all these processes as integral parts of overall land use planning. The model closely resembles project planning. It is a technique of envisioning end-states of alternative plans under some efficiency criteria. The justification for such a land use planning model lies in the philosophy that good planning depends on being able to successfully visualize what end products are intended, then planning a workable way of achieving these goals in time and space relationships.

The central perception of land use planning is that it should be conducted in the light of its role of providing pertinent information that will permit decision makers to judge and balance competing claims for scarce resources, and to select appropriate policy and management actions (Nygren, 1983).

Land use planning is a decision making process in a sociopolitical environment. The plan is an agreed upon course of action, which matches decision makers' perceptions of the problem and the collective compromises of past decisions, present conditions, and unreconciled goals of the people involved in planning (Nygren, 1983). Therefore, a land use plan is a compromised outcome in light of current development proposals, changes in technology, and changing public perception of needs and opportunities.

Decision making is often reactive, making immediate judgements based on information and tools available at the moment (Minicucci, 1983). Hence, land use planning should be a learning process and the model should be designed as an interactive decision making process.

Land Use Problems in Nepalese Hills

Nepal can be divided into three east-west geographical regions based upon topographical features. The Terai is the southern region, which is an almost flat extension of the Gangetic plain. To its north lies the Hills with elevation ranging from 600 to 5000 meters. The northern most region is called the Himalayan Mountains with elevations ranging from 5000 to 8839 meters (Mt. Everest). Terai, Hills, and Mountains ammount to 17, 68 and 15 percent of the total land area, respectively. The Terai economy consists of commercial agriculture and forestry. Most of the Himalayan Mountains are above the snowline and are important tourism resources. Most of the Hills have a subsistence economy. It is on the Hills region that this research study was focused.

A study of a Hill watershed (Fleming, 1983) estimated the average rate of forest disappearance to be 6 percent per year because of conversion of forest to scrub land, scrub land to open grazing land, and grazing land to terrace. This trend is the common ongoing land conversion at present in the Hills of Nepal.

From 1964 to 1974, the area of forest cleared for agriculture is estimated to be 672,000 ha in the Hills and 315,000 ha in the Terai plains (NPC,1974). A 1974/1975 land use statistics of Nepal (DFAMS,1977) shows that 34 percent of the total land area was in forest and 16.5 percent in cultivation (CBS, 1982). Nelson et. al. (1980) reported about 30 percent of Nepal as forested based on observations in 1977/1979. They estimated the reduction in forest taking place at 2 percent per year in the Hills (Middle Mountain Zone in their report). These statistics exhibit the magnitude of the land use conversion problem in the country.

The following phenomena explain the dynamics of land use changes in the Nepalese Hill areas:

1. Crops, livestock, and forestry together form integral parts of the existing subsistence farming system. Croplands produce food and animal feed; forest lands provide fodder for livestock and fuel for people; and livestock provides food, draught and manure. These interrelationships form a closely knit system exhibiting considerable resilience under fluctuating conditions. With a population growth rate of 2.6 percent per year, demand for food, fuelwood, fodder and timber is increasing every year. This increasing demand is having a severe impacts on the limited land resources.

2. Rugged topography and absence of transportation facilities make the Hills of Nepal remote from an urbanized market economy. Lack of transport necessitates that local demands for various products from the land be met by local production. Imports and exports of goods which would have substantial impact on land use patterns, are almost nonexistent and currently impossible.

3. The man-land ratio in the Hills cannot be expected to improve in the near future, because: (a) approximately 95 percent of the population depends upon agriculture for living; (b) urban employment is virtually unavailable to facilitate rural-urban migration at the present level of industrialization; (c) substantial reduction in the rural population is not expected in the near future even if the process of industrialization picks up; and (d) there are no more extensive areas of undeveloped land of agricultural potential remaining in the Terai plains for hill-plain migration. Terai migration had been one of the migration outlets for hill population untill two to three decades ago.

4. Agricultural production in Nepal has stagnated for the last two decades. During the period of 1975/76 to 1979/80, the annual rate of growth in food grain production has been around 1.3 percent (CBS 1982), which failed to keep pace with the population growth. The low production growth rate forces the growing population to cultivate submarginal lands, unsuitable for cultivation, causing serious soil erosion.

5. Almost all forest and range lands were nationalized in 1957 by the Private Forests Nationalization Act (Nepal Gazette, 1957). Private land is limited to cropland and homesteads only. The forest and rangeland are common property, which provide fuelwood, fodder and grazing. The usual overuse of common property resources is occurring. And also, the villagers have a strong incentive to destroy the forest and convert it to terraced land so they can claim it as private property (Wallace,1983; and Bromely and Chapagain, 1984).

6. The annual soil erosion rates in tonnes per hectare have been estimated as 8 for forest covered land, 15 for scrub land, 30 for grazing land, and 10 for terraced land (Fleming, 1983). While the trend of land conversion occurs through forest to cultivated terrace, the land is often left on poor forest cover (scrub) or open grazing for quite long period leading to overall degradation of land resources.

Food production is below the minimum nutritional requirement (Bajracharya, 1983); livestock feed availability is only half the desirable full ration (Shah,1980; Wyatt-Smith, 1982); and scarcity of fuelwood poses a major energy crisis (Eckholm, 1975; Mauch, 1976; FAO/World Bank, 1979) in the Nepalese Hills because of the preceding phenomena.

The Government of Nepal has been quite aggressive for the last decade and half in implementing renewable natural resource development programs in hill areas with internal and external resources effecting directly or indirectly the land use changes. Examples are: Resources Conservation and Utilization Project with United States Agency for International Development (USAID); Tinau Watershed Project with Swiss- German Technical Assistance; Integrated Watershed Management Project with Food and Agricultural Organization/United Nations Development Program (FAO/UNDP) and Finland Development Assistance; and Hill Forestry Project with Australian Development Assistance. The programs have been designed somewhat *ad hoc* partly because of the lack of land use planning rationales incorporating the interactions of all the integral components of a hill farming system and land resources. Improved land use planning models for rural development are needed because natural resource development activities will be increasing in the near future and because these programs will be more efficient if a consistent planning technique is used.

Justification For A Multiobjective Programming Model

The most relevant objectives of a land use plan for the Nepalese Hill areas are increasing land use products such as food, fodder, fuelwood; and decreasing environmental consequences such as soil erosion, and costs of labor and capital inputs. The achievement levels of these objectives provide the performance parameters of the alternative land use plans.

Most traditional planning models emphasize a single objective function as an optimizing criterion. The single objective function may be maximizing the net present value, minimizing costs, or maximizing a particular land use product. These single objective planning models do not seem adequate for the type of land use planning problem addressed in this study. A multiobjective decision making model is needed .

There are several reasons that demand a multiobjective decision making model. The most important are:

1. Prices of food, fodder and fuelwood do not exist. Valid and precise shadow price estimation is difficult or impossible. There does not exist a market for land use products like fodder and fuelwood. Very little exchange takes place for these goods either within the community or outside it. Therefore, price cannot be assigned to these products. This prevents applying optimization criteria for allocating the land to whichever uses command the highest value.

2. Land use products cannot be substituted for within the current production systems. Food, fodder and fuelwood are essential and complementary land use products in the

subsistence farming system. They should be considered as separate objectives for further reasons as follows:

(a) The households seek to attain as much food as possible by cultivating as much land as possible. Excess food, if any is produced, can be traded or sold for scarce cash. Hence, an increase in food production is an essential objective for land use planning.

(b) Livestock are an essential component, which provide manure, draught power, food in the form of meat and milk, hides and wool, and most important of all, the resilience of the system in the face of harvest fluctuations. Animals are sold in times of need and bought when good harvests permit. Hence, increase in fodder supply is also an important objective.

(c) Fuelwood is the only source of household energy. Energy is needed to cook food. Hence, increased supply of fuelwood represents another important objective. Allocating land for fuelwood production implies allocating land to forestry cover. And, because of many other possible advantages of forests, an increase in forest land is always considered ideal.

3. Cost of soil loss can not be estimated. Each land use plan must address the problem of soil erosion because it reduces future production possibilities and causes downstream flooding and sedimentation. There is no satisfactory means of expressing soil loss in value terms. It should not be compromised for the short term gains in other objectives. Hence, controlling the soil loss is an essential objective.

4. Attributes (objectives) of the land use plan can have unequal importance. Land use planning is a socio-political process. Decision makers (planners) often represent different sectoral interests. They allocate different weights to different objectives. For exam-

ple, a decision maker representing a financing agency would put heaviest weight on cost minimization, while an environmentalist might put heaviest weight on soil loss minimization. A multisectoral view of normative decision making is required to accommodate the heterogeneity and conflicting nature of the problem to reflect the participants' aspirations and priorities.

The above reasons demand that a suitable multiobjective programming model be developed to coordinate the individual objectives outlined above. It should generate sufficient information on trade-offs among objectives and their achievement levels so that judgement could be applied to the selection of competing plans.

It should prove to be an important model for thinking in policy and choice analysis, both by taking account of the wide variety of aspects inherent in planning problems, and by offering an operational framework for a multi-sectoral approach to practical choice problems. It is in this sense that an attempt to develop a multi-objective programming model for land use planning in the Nepalese Hills is justified.

Research Objectives

The general objective of this research is to develop a technique to provide decision guidelines for allocating land to competing uses for subsistence farming systems in the Nepalese Hill region. Following are the specific sub-objectives of the research:

1. To construct a multiobjective mathematical programming model, which generates sufficient information on achievement levels of objectives and their trade-offs.

2. To apply the model to land use planning with multiple objectives of increasing food grain, fodder, fuelwood, and decreasing soil loss and cost.

3. To test the completed model with data from a typical Nepalese Hill area on a commercially available personal computer software and examine implications for a watershed development project.

Chapter II

LITERATURE REVIEW ON MATHEMATICAL PROGRAMMING MODELS OF RURAL LAND-USE PLANNING

Literature on mathematical programming models, which directly relates to developing countries, is almost nonexistent. However, concepts and techniques developed in several diverse studies are found to be useful for various components of the proposed model. The modeling aspects of the studies in watershed development planning and multiple use forestry planning are particularly found to be most relevant. Linear programming (LP), integer programming (IP) and goal programming (GP) are the most widely used mathematical programming techniques in these models. Several land-use planning models also have adopted multiobjective programming (MP) techniques, as these techniques became available.

Watershed Development Planning

One of the multiple objectives in this study is reducing the soil loss through land use planning. Some of the watershed development LP models directly address the interrelationship between the soil erosion and land use changes. A "watershed firm" is conceptualized as an abstract decision making agent making planning decisions on the basis of both watershed and off-site benefits and costs (Timmons, 1954). A planning process utilizing the LP model is conceptualized for formulating optimal watershed programs by integrating and reconciling the interest of all participants (private farmers and public land use agencies) through the "watershed firm" (Pavelis et. al., 1961; and Anderson, Heady and Shrader, 1963). These studies examined the effect of land use changes on farm income of meeting *a priori* determined goals of soil erosion.

Later models evaluated the land use changes by examining explicit trade-off relationships between economic efficiency and environmental quality impacts (Narayanan and Swanson, 1972; Miller and Byers, 1973; Jacob and Timmons, 1974; and Harker and Michaelson, 1977). The models had economic objectives of maximizing net benefits or minimizing the cost of programs and the constraint on allowable off-farm soil loss. The models were formulated as LP problems and prescribed various optimal land use changes for parametrically varied allowable soil loss.

The studies by Narayanan and Swanson (1972), Jacob and Timmons (1974) and Harker and Michaelson (1977) used the Universal Soil Loss Equation (Wischmeir and Smith, 1965) and the sediment delivery ratio (Roehl, 1962 and Johnson and Moldenhauer, 1970). These studies formalized the interrelationships among land-use practices and hydrological systems providing a strong basis for the concept of the "watershed firm". Hence, the concept of the watershed as the planning area and the formulation of the objective function of reducing soil loss in the proposed model are supported by these studies.

All the above models dealt with cultivated agricultural land only. Hickman and Jackson (1979) studied economic consequences of imposing controls to limit soil loss from silvicultural activities. Kirby and Rupe (1987) studied the effect of timber harvest schedules on soil loss.

Multiple-use Planning

Multiple-use planning is a very popular phrase employed as the forestry counterpart of land-use planning and may be considered a subset of land-use planning (Leuschner, 1984). The foresters in the U.S. are generally interested in producing timber, water, recreation, hunting and grazing from the same forest. The problem of allocating forest land among these competing uses can, therefore, be perceived as the problem of land-use planning.

Linear Programming Models: Several studies discussed the possibility of using LP methods for management of a wildland area for multiple uses (Broido, McConnen, and O'Regan, 1965; Navon and McConnen, 1967; Ripley and Yandle, 1969; and Navon, 1971). Thompson et. al. (1973) and Turner (1974) described a process of generating information on trade-offs between products and economic goals for the manager to make decisions. Leuschner et. al. (1975) approached multiple-use planning as a process of matching a set of production objectives with a set of management activities that could be used to obtain those objectives and a set of constraints which limit the management activities. Sensitivity and post-optimality analysis were conducted to determine what parameters may be most sensitive to changes in the plan and to ascertain whether additional inventories in certain areas should be performed to examine the production trade-offs between different products and effects of absolute resource constraints upon the solution.

In these models the activities represented the average periodic inputs and outputs after a resource class had been brought to a stable state by a sequence of silvicultural treatments. Trade-off models emphasized multiple use interactions but lacked temporal treatments.

Navon (1971) designed the Timber RAM (Resource Allocation Model) for generating cutting and reforestation schedules for commercial lands under multiple-use management. Building on Navon's pioneering work, K. Norman Johnson developed the MUSYC (Multiple-Use Sustained Yield Calculation) technique, which was named Model II (Johnson and Scheurman, 1977). Non-timber uses of the forest are handled indirectly and essentially form constraints on timber production. In so far as the nontimber uses are effective at all, they merely limit land available for timber activities and limit the range of treatments that may be applied to timber production. Such a solution is not identical to one that would be expected if all goods and services of the forest were quantified within the objective function (Chappele, Mang and Miley, 1976).

Another model, the Resource Capability System (Watershed Development Unit, 1972 and Betters, 1978) attempted to provide a multi-resource, multiperiodic planning model and contained a number of response simulation routines to project the reaction of the forest to different management policies. Timber was treated as just another output. This model did not emphasize the details of timber management scheduling. Chappele, Mang and Miley (1976) suggested that linking Timber RAM with the Resource Capability System may improve the capability of Timber RAM for multiple-resource analysis by enabling the analyst to quantitatively examine alternative combinations of use for a specified land unit.

K. Norman Johnson and others (Johnson et. al., 1980) developed FORPLAN (FORest PLANning) as a means to integrate timber management planning into the main frame of integrated land use planning. The key to the integration of timber management and land management planning is the definition of decision variables. Whereas Timber RAM and MUSYC decision variables traced activities needed to produce timber through time, FORPLAN decision variables would trace "multiple-use" activities through time (Iversion and Alston, 1986 and Johnson, 1986).

These models differ in the minimum land grouping for which planning is performed and defining activities. In Timber RAM and MUSYC, each land grouping was called a "timber class", but FORPLAN has two categories, "analysis area" and "aggregate emphasis zone". Activities for the management of land were called "management alternatives" in Timber RAM and MUSYC. FORPLAN called them "prescriptions". Management alternatives may be accomplished within one planning period or may span many periods. Prescriptions, however, trace the consequences of the activities throughout the planning horizon.

FORPLAN defines prescription by "aggregate emphasis". Each prescription represents a particular management emphasis (such as timber/wildlife or wildlife/recreation) and a management intensity. The set of prescriptions with particular aggregate emphasis provides the alternative choices for aggregate emphasis zones. An "aggregate emphasis zone" is a composite of analysis areas. Selection of a specific aggregate delimits the set of prescription choices for the strata-based analysis areas covered by the aggregate emphasis zone.

FORPLAN without aggregate emphasis provides decision variables as choices for treatment of individual areas. The inclusion of aggregate emphasis provides choices both in the broader allocation of land and in the narrower assignment of prescription treatments to the land. Effectively, the model structure is one of choice within choice.

Although FORPLAN enhanced the ability to track multiple resource outputs and consider land allocation decisions through time, it is still besieged with problems. Stuart and Kent (1982) pointed out the problems of model size and difficulty in generating spatially reasonable land allocations and activity schedules.

Mixed integer-linear programming which treats aggregate emphasis areas as integer variables has been suggested to solve this problem. IP allows only one prescription to be selected for each zone (Jones and Schuster, 1985). It is sufficiently small to be processed on a small computer. The main disadvantage is that only a limited number of management alternatives (prescriptions) can be handled effectively, making it best suited to problems of relatively small geographic scope. An additional advantage is the enhanced capability to conduct sensitivity analysis. Earlier Nautiyal, Ngo and Thadany (1975) applied mixed-integer programming to a land-use planning problem.

The LP models of solving the multiple objective problems reviewed here can be commonly described as the "constraint method" (Cohon, 1978), where one of the objectives is optimized while appending the other objectives to a constraint set. The problem in this approach lies in identifying which objective to consider genuine for the objective function. This method also assumes the objectives stated as constraints have equal relative importance.

Goal Programming Models: Several GP models have been formulated in forestry planning problems to accommodate multiple goals simultaneously. GP was first discussed in the forestry literature by Field (1973), to solve a land-use planning problem. Most of the literature on application of GP to land-use planning discusses various methods of determining the values associated with the goal levels and priority rankings or weightings established to reflect the relative importance of the various goals.

Field (1973) evaluated the goal programming algorithms presented by Charnes and Cooper (1961) and Lee (1972), and finding limitations in both techniques, he developed an alternative algorithm, the "Priority Factor Algorithm". Field's Priority Factor algorithm converted ordinal ranks into cardinal weights and had the advantages of allowing the use of existing linear programming packages (such as IBM's MPSX). Later, Arp and Lavigne (1982) also adopted this algorithm in a general goal programming procedure for hierarchical multiple land-use planning of forested lands with variable planning horizons. Bell (1976) proposed the Churchman-Ackoff (1954) technique to obtain relative weights for the deviational variables in the GP objective.

The use of ordinal ranking has its serious limitations on post-optimality analysis. No meaningful interpretation can be placed on an objective function value or on the shadow values for a problem involving the minimization of aggregate deviation from goals (Field,1973). There is no way to infer marginal trade-offs among goals. Unit deviation from higher ranking goal target levels is infinitely more undesirable than unit deviation from lower ranked goal target level (Dyer et. al., 1979).

The hierarchical goal programming often results in a very restrictive solution. Schuler and Meadows (1975), and Schuler, Webster and Meadows (1977) generated trade-off information in terms of percent goal underachievement as the budget levels and management strategies were changed to overcome this disadvantage. Dane, Meador and White (1977) produced several alternative acreage allocations by shifting weights on under and over-production of various goals. These models are an interactive rather than hierarchical ordering. Chang and Buongiorno (1981) adopted the preemptive ordinal priorities to those goals whose relative importance cannot be measured by an exact number to establish an ordinality of goals and cardinal weights.

In the literature reviewed so far goal target levels have been specified *a priori*. Field (1973), Schuler and Meadows (1975), Bottoms and Bartlets (1975), and Arp and Lavigne (1982) set goals to levels intuitively established by themselves or by management. Dane, Meador and White (1977) set the current levels of the goals as target levels. Bell (1976) and Chang and Buongiorno (1981) set the goals to tentative levels. Bell suggested varying the target levels to test sensitivity to the solution and modify them if they were unrealistically low or high. Chang and Buongiorno suggested several trial and error runs on the set of goal levels. These results provide input in their model combining the GP with an Input-Output model untill they match the set of the final demands for forest outputs.

Dyer et. al (1979) has shown that these approaches would possibly result in dominated or inferior solutions. Bell (1976) suggested setting the target level of one of the goals to an arbitrarily very large value. While not leading to the generation of dominated solutions, this approach overstates the actual deviation of the final solution from the single objective optimal level. Repeated parametric runs may provide some indication of the nondominated solution frontier. However, setting all goal levels at the nondominated solution frontier would be parametrically impossible. In cases, where the mathematical programming matrix contains numerous rows, especially with temporal goals such as timber harvest scheduling, the sensitivity analysis necessary to define even a small part of the nondominated solution frontier with any confidence would be a staggering task at best.

Kao and Brodie (1979) and Field, Dress and Fortson (1980) used LP solutions to individual objectives as goal levels. This approach overcame the problem of infeasible specification and satisfied alternative criteria in cases with multiple optima. Later, Hotvedt, Leuschner and Buyoff (1982) and Walker (1985) also adopted this approach of setting goal levels.

Hotvedt et. al. (1982) developed a heuristic, "unstructured" weight determination procedure for harvest scheduling models using the complementary linear and goal programming approach. The procedure was designed as an interactive method, in which decision makers were provided with information on goal achievement level and trade-offs under different weight structures. The unstructured approach was adopted based on the impression that it was found acceptable to decision makers because of its simplicity in understanding the process. All weights were proportioned so as to approximately sum to 100. The goals were not scaled or normalized. Thus, the weights themselves did not reflect a preference function *per se*. The weight structure followed an attempt to use the transitivity axiom of ratio choice in specifying the alternative weight structure. Assigning "reasonable" weights under the transitivity axiom led to a certain degree of insensitivity in the resulting solution sets. This led to the testing of very large and very small weight combinations. The choice of weight structures tested eventually became somewhat arbitrary. However, the procedure presents an operational process for using GP interactively.

Multiobjective Programming: Kuhn and Tucker (1951) and Koopmans (1951) developed the vector optimization theory, the mathematical programming models with more than a single objective function. For the last two decades, a great deal of effort has been devoted to the development of solution techniques for vector optimization problems. Steuer and Schuler (1978 and 1981) and Allen (1986) have attempted to apply vector optimization techniques to forestry planning.

Steuer and Schuler (1978 and 1981) devised an interactive multiple objective linear programming approach. In this approach a decision maker does not have to specify any weights. This method presents to the decision maker 2K+1 nondominated extreme points at each iteration (K is the number of objectives); the decision maker has only to indicate the most preferable solution from this set. Once this solution is identified, the nondominated extreme points in the neighborhood are explored and a new set of 2K+1 nondominated solutions are identified and presented to the decision maker. The analyst's mathematical tools include (1) linear programming; (2) an (objective function) gradient cone construction technique; (3) a vector-maximum algorithm; and (4) a device for filtering extreme point solutions.

Cohon and others (1979) modified the weighting method of solving multiple-objective problems and called it the non-inferior set estimation (NISE) method. The method was developed to converge quickly in a good approximation of the noninferior set. In addition, the accuracy of the approximation can be controlled in the NISE method through a predetermined error criterion. Allen (1986) applied the NISE method to a problem of forestry management in Tanzania. NISE method is simple. The method involves solving N+2 linear programs to provide an approximation of the noninferior set consisting of N solutions. However, for the problems with more than two objectives, the computational complexity is increased.

The studies on LP, GP, and MP models provide the various approaches to modeling the multiple objectives. The proposed model is formulated as a MP model. The MP approach was chosen because (1) all the multiple objectives could be expressed in a single composite objective function, and (2) the achievement levels of the objectives as well as their trade-offs could be studied.

In summary, the proposed model synthesizes watershed development planning, multiple use forestry planning, and harvest scheduling models previously developed. It takes parts from each and combines to provide solutions in developing nations where there are non-market, subsistence farming economies.

Chapter III

METHODS AND MATERIALS

This chapter presents the theoretical multi-objective programming model, the applied land use planning model, and data construction for implementing the applied model in a representative Nepalese Hills watershed.

Theoretical Model

A multi-objective programming problem is represented as a vector optimization problem (VOP):

$$\text{Optimize } Z(\mathbf{x}) = \{\max Z_1(\mathbf{x}), \ldots, \max Z_p(\mathbf{x}), \min Z_{p+1}(\mathbf{x}), \ldots, \min Z_r(\mathbf{x})\}$$

$$\text{s. t. } \mathbf{x} \in \mathbf{X}$$

where, $Z_q(\mathbf{x}) = C_q\mathbf{x}$, $q = 1, \ldots, p$ are the maximizing single objective functions and $Z_s(\mathbf{x}) = C_s\mathbf{x}$, $s = p + 1, \ldots, r$ are the minimizing single objective functions. C_q and C_s are the respective objective function coefficient vectors; **X** is the feasible region; $\mathbf{X} = \{\mathbf{x}: \mathbf{x} \in R^n \,!\, \mathbf{Ax} \le \mathbf{b}\ ,\ \mathbf{x} \ge \mathbf{0}\ ,\ \mathbf{b} \in R^m\}$; $\mathbf{x} = (x_1, x_2, \ldots, x_n) \in R^n$; n is the number of decision variables, m is the number of constraints; **A** is the coefficient matrix; and **b** is the constraint vector.

An optimal solution can not be found to the problem without information about preferences which provides a rule for combining the objectives. The objectives are incommensurable and at least some solutions (alternatives) are therefore incomparable. A complete ordering (comparison) can be obtained for a vector optimization only by introducing value judgements into the solution process (Cohon and Marks, 1975).

Previous Solution Techniques : Substantial theories, concepts and techniques of eliciting preference have been developed during the last two decades and have been reviewed extensively (Cohon and Marks, 1975; Cohon, 1978; Hwang and Masud, 1979; Zeleny, 1982; Goicoechea, Hansen and Duckstein, 1982; Changkong and Haimes, 1983; Szidarovsky, Gershen, and Duckstein, 1986; and Steuer, 1986).

Traditionally there are two approaches for solving the VOP - the weighting method and the constraint method (Cohon, 1978). For the weighting method, the problem is in determining the proper weight for individual objective functions where a composite objective function is formed as an additive form of all individual objective functions. The weights are sensitive to the level of the individual objectives as well as the level of all other objectives (Hwang and Masud, 1979). For the constraint method, the problem becomes complex and it becomes difficult to choose the acceptable levels of the constraints, because of the incommensurability and the conflicting nature of the multiple criteria (Hwang and Masud, 1979).

Several techniques have been suggested to eliminate the difficulties of both methods. Differences in the various techniques are due to the types of preference information articulation from the decision makers (DM). The method of global criterion (Boychuk and Ovchinnikov 1973, as cited by Hwang and Masud, 1979; Salukvadze, 1971, 1972, and 1974; and Sen, 1984) does not need articulation of preference information once the problem constraints and objectives have been defined. A major disadvantage of this method is that the analyst makes assumptions about the DM's preferences.

Utility function methods (Fishburn, 1974; Winterfeldt and Fischer, 1975; Keeney and Raiffa, 1976; and Farquhar, 1977), the lexicographic method (Waltz, 1967) and goal programming

(Charnes and Cooper, 1961; Ijiri, 1965; Lee, 1972; and Ignizio, 1976) need *a priori* articulation of cardinal or ordinal preferences. The major difficulty with these methods is that the DM is required to articulate preference judgement in an information vacuum.

With the concept of decision making as an interactive process, several techniques have been developed for progressive articulation of preference information. Methods of Geofrion, Dyer and Feinberg (1972), Haimes and Hall (1974), and Zionts and Wallenius (1976) and interactive goal programming (Dyer, 1972) use trade-off information.

These methods construct overall preference or utility functions through a series of questions regarding the preference trade-offs on a specific achievement level of the objectives. The trade-offs are generally valid only over a narrow range of objective values which are not indicated clearly to the decision makers. Thus the use of preference or utility functions requires DMs to articulate value judgements with incomplete information. They will not have knowledge of the feasible trade-offs between objectives at a nondominated set or the implication of their decision for project design (Cohon and Marks, 1975).

Freeman (1969) has pointed out that inferring preference from past decisions alone is inappropriate because those decisions were made in the absence of knowledge of the nondominated set. Also, it is often difficult for users to reverse weighting decisions once they have been made, without restarting the algorithms. Zeleny (1982) emphasized the approach of presenting nondominated solutions to the DM and allowing him to retrace, follow different paths, or use trial and error to progressively develop new relative preference structures.

STEM (Benayoun et. al., 1971), SEMOPS (Monarchi et. al., 1973), and the method of Displaced Ideal (Zeleny, 1973, 1974, 1976 and 1982) in general find a nondominated solution, get DM's reactions to this solution, and modify the problem accordingly. The trade-off information is implicit. These methods assume that the DM is more confident in indicating an acceptable achievement level of objectives than in indicating preferred trade-offs.

MOLP techniques (Evans and Steuer, 1973; and Yu and Zeleny, 1975) generate all the extreme point solutions in linear cases. These techniques cannot be solved with a commercial LP package. The number of all the extreme point solutions may be large even for a small practical problem. It is not desirable to present all the extreme point solutions to the DM for their interaction.

Steuer (1977), Steuer and Schuler (1978), Morse (1978), and Torn (1980) developed a series of filtering and clustering techniques for progressive reduction of the number of nondominated solutions. All of these methods are complex and need special computer packages. The NISE method (Cohon, 1979) converges on a good approximation of the nondominated set and can generate information on explicit trade-off between objectives as well as their achievement levels. The method is limited to a problem with only two objectives.

A Proposed Solution Technique : This study uses a different approach. A weighted sum achievement level ratio function, which aggregates all the objective functions into a single composite objective function, is developed. The composite function is:

$$R(\mathbf{x}) = \sum_{q=1}^{p} \lambda_q R_q(\mathbf{x}) - \sum_{s=p+1}^{r} \lambda_s R_s(\mathbf{x})$$

where,

$$R_q(\mathbf{x}) = \frac{Z_q(\mathbf{x})}{Z_q(\bar{\mathbf{x}})}$$

$$R_s(\mathbf{x}) = \frac{Z_s(\mathbf{x})}{Z_s(\bar{\mathbf{x}})}$$

and $\sum_{q=1}^{p} \lambda_q + \sum_{s=p+1}^{r} \lambda_s = 1 \,;\, 1 \geq \lambda_q \,,\, \lambda_s \geq 0$

$Z_q(\bar{\mathbf{x}})$ and $Z_s(\bar{\mathbf{x}})$ are the current production levels of the respective objective functions $Z_q(\mathbf{x})$ and $Z_s(\mathbf{x})$ at the time the plan is made; λ_q and λ_s are the weighting coefficients reflecting the relative importance of the respective achievement level ratios $R_q(\mathbf{x})$ and $R_s(\mathbf{x})$. An interactive technique of assigning the weighting coefficients is also developed in this study.

When the values of the weighting coefficients are assigned, the best solution for the problem is determined by solving the following problem:

$$\max \ R(\mathbf{x}) = \sum_{q=1}^{p} \lambda_q R_q(\mathbf{x}) - \sum_{s=p+1}^{r} \lambda_s R_s(\mathbf{x})$$

$$\text{s. t. } \mathbf{x} \in \mathbf{X}.$$

This model has the following characteristics:

1. It generates non-dominated solutions.

2. It generates information on trade-offs between objectives and their achievement levels.

3. It articulates preferences based upon the information on trade-offs between objectives as well as their achievement levels.

4. It reduces choice solutions to a managable subset through an interactive weighting technique.

Each of these characteristics are described below.

Non-dominance : A set of non-dominated solutions is sought in a multiobjective programming problem instead of a single optimal solution. The general concept of a non-dominated solution is found in the economics literature as "pareto-optimum" and "productive efficiency" (Koopmans, 1951). It is found in operations research as necessary and sufficient conditions for a "proper" solution to a vector optimization problem (Kuhn and Tucker, 1951), and as a "noninferior solution" (Zadeh, 1963). A solution is non-dominated if there is no other solution which improves at least one objective function without worsening any other.

Zeleny (1982) comments on the importance of non-dominated solutions. If more is always preferable to less, then any solution which maximizes the utility function of a rational DM must be nondominated. Reliable construction of a utility function may be too complex, unrealistic, or impractical. The set of nondominated solutions provides meaningful alternatives. If non-dominated solutions to a problem can be reduced to a relatively manageable number of solutions or alternatives of choice, then all of the nondominated solutions can be evaluated. This approach provides an alternative way to model decision making without constructing a utility function.

Cohon and Marks (1975) and Cohon (1978) have shown that solutions generated by weighted additive functions form the nondominated solution set in objective function space corresponding to that in decision space. Hence, the solutions generated by the weighted sum achievement level ratio function are nondominated in objective function space and decision space.

Trade-offs : The trade-off between any two solutions is a measure of how much of objective $Z_1(\mathbf{x})$ must be sacrificed for a given increase in objective $Z_2(\mathbf{x})$, on average, in moving from one solution to the other. Cohon and Marks (1979) used the relative objective function weights to interpret trade-offs between any two solutions as the value of the slope $(\frac{\lambda_1}{\lambda_2})$.

For the achievement level ratio function, the trade-off value or the weighted marginal rate of substitution is computed as

$$T(Z_1(\bar{\mathbf{x}}), Z_2(\bar{\mathbf{x}})) = -\frac{\lambda_1 Z_2(\bar{\mathbf{x}})}{\lambda_2 Z_1(\bar{\mathbf{x}})}$$

where, $T(Z_1(\bar{x}), Z_2(\bar{x}))$ is the value of $Z_1(x)$ sacrificed to increase one unit of $Z_2(x)$ for a particular nondominated solution.

Information on trade-off and achievement levels of objectives for the nondominated solutions provide guidelines to the DM for applying consistent judgement in selecting the best solution.

Preference Articulation : Maximizing a ratio $R_q(x) = \frac{Z_q(x)}{Z_q(\bar{x})}$, where, $R_q(X) \geq 1$, $Z_q(x)$ is the maximizing single objective function, and $Z_q(\bar{x})$ is the current level of production of that objective function, is maximizing the achievement level of that objective from the current value. A relative importance weight on the ratio provides the notion of how important the increase in achievement level of that objective function is in relation to the increase or decrease in the achievement level of other objective functions.

$Z_q(\bar{x})$ is the reference level, against which the increase or decrease in the achievement level in future is judged by the DM. It is easier to visualize than other types of references, such as artificial goals, because people are experiencing that level now.

Hwang and Masud (1979) show that a particular preference structure (indifference curve) can be articulated by a hyperplane defined by the normalized weight coefficients representing the relative importance of the objective functions. The orientation of the hyperplane changes when the normalized weight coefficients are changed. Hence, a subset of nondominated solutions can be generated by maximizing a series of hyperplanes defined by the selected sets of the weight vector.

Interactive Weighting Technique : DMs are often unable to specify an *a priori* set of relative weights for the achievement level ratios. Some procedures are necessary which allow for progressive articulation of weights through an interaction process. The procedure should allow the DM to gain a greater understanding and feel for the structure of the problem.

Aspirations and desires change as a result of learning and experience. A solution to a decision problem is an acceptable course of action. Acceptability is a compromise involved in selecting the best among the available choices. If choices presented are satisfactory, the process can be considered credible.

An interactive search technique is developed to find out the best solution to a five objective (multiple objectives) programming problem. The technique consists of at least three interactions. The first interaction ranks the objectives ordinally. The second interaction reveals the weight structure of the ranked objectives. And, the third interaction selects the best of the solutions generated by a set of cardinally defined relative importance weights. These interactions are repeated until the DM finds the acceptable solution.

The first interaction asks the DM to rank the five objectives ordinally in order of importance. Let us suppose the DM ranks them in the following order:

$$a > b > c > d > e$$

where, a, b, c, d, and e represent the functions optimizing the achievement level ratios. Then the analyst extrapolates all possible preference relationships among objectives for the selected ranking. These preference relation are listed in Table 1. They are defined either as equal to or greater than the next objective succeeding the higher ranked objective.

Table 1. Preference relationships for the ranking

$a > b > c > d > e$

S.No.	Preference relationship
1	$a > b > c > d > e$
2	$a = b > c > d > e$
3	$a > b = c > d > e$
4	$a > b > c = d > e$
5	$a > b > c > d = e$
6	$a = b > c = d > e$
7	$a = b > c > d = e$
8	$a > b = c > d = e$
9	$a = b = c > d > e$
10	$a > b = c = d > e$
11	$a > b > c = d = e$
12	$a = b > c = d = e$
13	$a = b = c > d = e$
14	$a = b = c = d > e$
15	$a > b = c = d = e$
16	$a = b = c = d = e$

The second interaction asks the DM to select a weight structure that the DM thinks most closely elicits the best solution. Let us suppose the DM selects the following weight structures:

$$a > b = c > d = e.$$

Weights (W_i) are then attachecd to each objective and are given discrete values ranging from 1 to 5. The value of the weight of the less preferred objective is lower than the weight of the more preferred objective. Any weight can take any value from 1 to 5 if consistent with the preference relation. The characteristics of the chosen scale will be discussed later in chapter V. Cardinal weight structures are developed from this weighting scale. A corresponding relative importance weight is computed for each objective for each weight structure by the relation:

$$\lambda_i = \frac{W_i}{\sum_{i=1}^{5} W_i}, \qquad i = a, b, \ldots, e.$$

where, λ_i = relative importance weight and W_i = weight structure value.

The total number of relative importance weights that the preference relationship can have ranges from one to ten. The list of all possible cardinal weight structures and corresponding relative importance weights to this preference relation are shown in Table 2.

Solutions for these sets of relative importance weights are presented to the DM. The solutions contain information on various trade-offs between respective objectives and their achievement levels. The DM selects one solution, which he/she thinks the best alternative. This interaction procedure provides DM opportunity to learn about and compare various probable candidate solutions within the chosen rank and preference relation. If the DM is not satisfied with this outcome, the process can continue again from any level of interaction.

Table 2. Weight structures and relative importance weights for the selected preference relation.

S. No.	Weight Structure (W_a, W_b, W_c, W_d, W_e)	Relative Importance Weights ($\lambda_a, \lambda_b, \lambda_c, \lambda_d, \lambda_e$)
1	5,4,4,3,3	$\frac{5}{19}, \frac{4}{19}, \frac{4}{19}, \frac{3}{19}, \frac{3}{19}$
2	5,4,4,2,2	$\frac{5}{17}, \frac{4}{17}, \frac{4}{17}, \frac{2}{17}, \frac{2}{17}$
3	5,4,4,1,1	$\frac{5}{15}, \frac{4}{15}, \frac{4}{15}, \frac{1}{15}, \frac{1}{15}$
4	5,3,3,2,2	$\frac{5}{15}, \frac{3}{15}, \frac{3}{15}, \frac{2}{15}, \frac{2}{15}$
5	5,3,3,1,1	$\frac{5}{13}, \frac{3}{13}, \frac{3}{13}, \frac{1}{13}, \frac{1}{13}$
6	5,2,2,1,1	$\frac{5}{11}, \frac{2}{11}, \frac{2}{11}, \frac{1}{11}, \frac{1}{11}$
7	4,3,3,2,2	$\frac{4}{14}, \frac{3}{14}, \frac{3}{14}, \frac{2}{14}, \frac{2}{14}$
8	4,3,3,1,1	$\frac{4}{12}, \frac{3}{12}, \frac{3}{12}, \frac{1}{12}, \frac{1}{12}$
9	4,2,2,1,1	$\frac{4}{10}, \frac{2}{10}, \frac{2}{10}, \frac{1}{10}, \frac{1}{10}$
10	3,2,2,1,1	$\frac{3}{9}, \frac{2}{9}, \frac{2}{9}, \frac{1}{9}, \frac{1}{9}$

Applied Model

Conceptualizing the multi-objective programming model for land use planning in the Nepalese Hills involves defining decision variables, and formulating constraints and objective functions. These components of the model are built upon the following structure:

1. The plans are formulated for a planning horizon of 25 years.

2. The planning horizon consists of 5 year planning periods, therefore 5 planning periods in 25 years.

3. The planning area is divided into planning units. A planning unit is the area, on the ground, that will be allocated to one or more land use sequence. A planning unit is an area under the current land use on a particular land class defined below.

4. A land use sequence specifies the periodic operations on a planning unit. It specifies in which period the land use conversion takes place. It also specifies the periodic operations such as planting (afforestation), harvesting, and other intermediate operations, if any. A series of land use sequences are defined for each planning unit.

Decision variables and some constraints in this model are derived by manipulating the Timber Harvest Scheduling Model I (Johnson and Scheurman, 1977). The model generally follows the Model I structure.

Decision Variables : The problem is to determine what land use to implement on which land and when. The decision variable is the number of hectares of a certain planning unit allocated to a specific land use in a specific planning period. Therefore, decision variables are defined as:

x_{lq} = the hectares of planning unit l assigned to land use sequence q

where, $l = 1, \dots, u$; $q = 1, \dots, R_l$; u is the number of planning units and R_l is number of land use sequences defined below.

Constraints : Two types of constraints are employed. One is a set of resource constraints. Two kinds of resource constraints are recognized:- (i) Initial area constraints and (ii) Irrigation potential area constraints. The other is a set of policy constraints. Two kinds of policy constraints are imposed:- (i) Periodic achievement constraints and (ii) First period achievement constraints.

An initial area constraint is

$$\sum_{q=1}^{R_l} x_{lq} \leq A_l$$

where, A_l = Initial hectares in planning unit l .

An irrigation potential area constraint is

$$\sum_{q=1}^{R_l} x_{lq} \leq I_{lj}$$

where, I_{lj} = Hectares which could be irrigated in planning unit l in planning period j.

Food, fodder, fuelwood, cost and soil loss are the five outputs of concern in this model. A policy is adopted for land use planning in this model such that achievement levels on food, fodder, and fuelwood should increase each period at least by a certain percent of the previous period and achievement levels of cost and soil loss should decrease below a certain percent of that of the previous period. These policy constraints are:

$$FOOD_{j+1} - (1 + \alpha)FOOD_j \geq 0$$

$$FOOD_{j+1} - (1 + \beta)FODD_j \geq 0$$

$$FUEL_{j+1} - (1 + \gamma)FUEL_j \geq 0$$

$$COST_{j+1} - (1 + \theta)COST_j \leq 0$$

$$SOIL_{j+1} - (1 + \tau)SOIL_j \leq 0$$

where, α, β, and γ are the minimum periodic growth rates of food, fodder and fuelwood productions. θ and τ are the maximum allowable periodic increase rates.

The second policy constraint requires defining the objective functions for any period j. They are:

$$FOOD_j = \sum_{l=1}^{u} \sum_{q=1}^{R_l} FOOD_{lqj}\ x_{lq}$$

$$FODD_j = \sum_{l=1}^{u} \sum_{q=1}^{R_l} FODD_{lqj}\ x_{lq}$$

$$FUEL_j = \sum_{l=1}^{u} \sum_{q=1}^{R_l} FUEL_{lqj}\ x_{lq}$$

$$COST_j = \sum_{l=1}^{u} \sum_{q=1}^{R_l} COST_{lqj}\ x_{lq}$$

$$SOIL_j = \sum_{l=1}^{u} \sum_{q=1}^{R_l} SOIL_{lqj}\ x_{lq}$$

where, $FOOD_{lqj}$ = Food production per hectare in period j from planning unit l under land use sequence q.

$FODD_{lqj}$ = Fodder production per hectare in period j from planning unit l under land use sequence q.

$FUEL_{lqj}$ = Fuelwood production per hectare in period j from planning unit l under land use sequence q.

$COST_{lqj}$ = Cost per hectare in period j for planning unit l under land use sequence q. These costs include annual production cost and land use conversion cost.

$SOIL_{lqj}$ = Soil loss per hectare in period j from the planning unit l under land use sequence q.

The second policy constraints are the first period achievement level constraints. They are:

$$FOOD_1 = 5FOOD_0$$

$$FODD_1 = 5FODD_0$$

$$FUEL_1 = 5FUEL_0$$

$$COST_1 = 5COST_0$$

$$SOIL_1 = 5SOIL_0$$

$FOOD_0$, $FODD_0$, $FUEL_0$, $SOIL_0$, $COST_0$ are the current level of annual output of the respective objectives.

Objective Function : The composite objective function is a maximizing weighted sum achievement level ratio function with appropriate signs on the respective ratios.: The composite objective function is:

$$\max Z = \lambda_a \frac{FOOD}{\overline{FOOD}} + \lambda_b \frac{FODD}{\overline{FODD}} + \lambda_c \frac{FUEL}{\overline{FUEL}} - \lambda_d \frac{COST}{\overline{COST}} - \lambda_e \frac{SOIL}{\overline{SOIL}}$$

where, $FOOD = \sum_{j=1}^{N} FOOD_j$

$$FODD = \sum_{j=1}^{N} FODD_j$$

$$FUEL = \sum_{j=1}^{N} FUEL_j$$

$$COST = \sum_{j=1}^{N} COST_j$$

$$SOIL = \sum_{j=1}^{N} SOIL_j$$

and $\overline{FOOD} = 5FOOD_1$

$$\overline{FODD} = 5FODD_1$$

$$\overline{FUEL} = 5FUEL_1$$

$$\overline{SOIL} = 5SOIL_1$$

$$\overline{COST} = 5COST_1$$

N is the number of planning periods in a planning horizon. $FOOD$, $FODD$, $FUEL$, $COST$, and $SOIL$ are the respective total achievement levels for the planning horizon. These are the single objective functions, otherwise. λ_a, λ_b, λ_c, λ_d, and λ_e are the relative importance weights assigned to the respective ratios. $\overline{FOOD}$, $\overline{FODD}$, $\overline{FUEL}$, $\overline{COST}$, and $\overline{SOIL}$ are the achievement levels of the objectives at the current level for the planning horizon.

LP Problem : Since the constraints and the objective functions are linear the model can be formulated as an LP problem. One of the objective of this study is to develop the model of a size that could be run on a personal computer, for ready export to a developing nation. Hence, the size of the model is an important consideration. The size of the problem depends upon the number of constraints and number of decision variables. The number of constraints depends upon the number of planning units, number of planning periods, and specific resource and policy constraints. The number of decision variables depends upon the number of planning units and number of land use sequences.

Data Construction

For each set of relative importance weights of the composite objective function, the following data are required to run the model:

1. The values of the right hand side (RHS) on area constraints, A_i.
2. The values of the RHS on irrigation potential area constraints I_{ij}.
3. The values of the constraint coefficients $FOOD_{iqj}$, $FODD_{iqj}$, $FUEL_{iqj}$, $COST_{iqj}$, and $SOIL_{iqj}$ for the **A** matrix.
4. The values of RHS on First period achievement level forming policy constraints, $FOOD_1$, $FODD_1$, $FUEL_1$, $COST_1$, and $SOIL_1$.
5. The values for the periodic output coefficients α, β, γ, θ and τ
6. The values of the denominators in the composite function, $\overline{FOOD}$, $\overline{FODD}$, $\overline{FUEL}$, $\overline{COST}$ and $\overline{SOIL}$.

Data on both area constraints (1 and 2 above) are the available hectares in each planning unit. They can be computed from the current land use maps and land capability classification maps.

The constraint coefficients $FOOD_{lqj}$, $FODD_{lqj}$, $FUEL_{lqj}$, $COST_{lqj}$, and $SOIL_{lqj}$ (3 above) are developed from average yields of food, fodder, fuelwood, costs of their production and consequent erosion rates from various land uses within the watershed.

The values of the RHS on policy constraints (4 above) can be computed once the area constraints and constraint coefficients are determined. They are computed by multiplying the summed annual food, fodder and fuelwood productions, cost and soil loss incurred in the watershed for the current land use by the number of years in a planning period.

The values for α, β, γ, θ and τ (above) are assigned subjectively reflecting the periodic growth rate policy. The values for the denominators in the composite function (6 above) are the first period achievement levels multiplied by the number of planning periods in the planning horizon.

Land classification and land use options play an important role in derivation of values for area constraints and constraint coefficients (1,2 and 3 above). Hence, a brief discussion on them is provided below.

Land classification : Average yields, costs, and soil erosion rates vary by land class because of the spatial variations in physiograpic characteristics and soil properties. The ideal approach would be classifying the planning units according to their average yield potentials for major crops. This information is not available at present. Therefore, this study will adopt the best land classification system available for the study area.

In general, there are many different systems of land classification, each classifying the land according to some specific objective. In the United States of America, soil surveys made on the basis of soil taxonomy contain a soil map, a description of each mapping unit, and predicted responses of each mapping unit for a wide variety of land uses. The most widely used system of relating soil mapping units to land use planning is that of the United States Department of Agriculture (Soil Survey Staff, 1975), which lists land capability classes. A standard land evaluation technique is being attempted by Food and Agriculture Organisation (FAO, 1976 and 1984) for rural land use planning in developing countries.

However, these systems provide only qualitative statements of production potentials. They do not provide quantitative yield estimates for various crops. This may be because this information becomes invalid in the long run, due to changing technology of production.

Land classification systems based upon quantitative yield estimates are used in forestry, however. Timber management uses site quality indices which is defined as "timber production potential of a site for a particular species or forest type" (Clutter et. al., 1983). Carmean (1975) presents reviews on many forest site evaluation methods, which relate timber production with soil and topographic factors. However, a satisfactory system of site evaluation for multiple-use management in forestry is yet to be developed.

Land capability classification prepared by Impat (1980) is used as the basis for delineating the planning units and extrapolating necessary quantitative yield estimates in this study. Impat interpreted the soils in Phewa-tal watershed for various land uses within their capabilities to minimize the risk of soil erosion. Some of the key factors are the soil depth and texture, the land slope, and the past erosion. Parent materials, permeability, fertility and a few chemical properties are also considered wherever these factors play an important role. In the hilly areas, slope is the most dominant land characteristic. A land capability map is produced by overlaying the slope map on the soil map and then land capability classes are delineated. Sthapit (1985) has extended the land classification system for Nepalese Hill areas. Impat's land classification is adopted for this study because of the availability of field data for the Phewa-tal watershed.

There are nine land capability classes.

Class I Slope up to 3 percent, soil depth more than 15 cm, no limitations of stony, wet, or severe erosion (SWE) characteristics, suitable for cultivation, no conservation measures required.

Class II Slope between 3 - 15 percent, soil depth more than 15 cm, no SWE limitations, suitable for cultivation, requires no or less intensive conservation measures.

Class III Slope between 15 - 40 percent, soil depth more than 15 cm, no SWE limitations, suitable for cultivation, requires intensive conservation measures, e.g. bench terrace.

Class IV Slope approaching 40 percent, soil depth less than 40 cm or SWE limitations,suitable for pasture.

Class V Slope between 40 - 60 percent, soil depth more than 70 cm, suitable for fruit orchard, requires terracing.

Class VI Slope 60 - 80 percent, suitable for silvi-pasture.

Class VII Slopes over 60 percent or from 40 percent up where soil depth is limiting or SWE limit is encountered, suitable for forest and fodder trees.

Class VIII Slopes over 80 percent, suitable for protection forest.

Class IX Waste land and others.

This classification is very restrictive as the suitability criteria are based on which crop can do best on a given land unit with minimum soil erosion hazards. The suitability is also a qualitative judgement. In absence of better information, these classes are used as the basis for accounting the spatial variation in average yields of the crops that occur due to differences in the physical characteristics of the land.

Land Use Options : Land use options are the most significant alternative land uses considered for planning. The land use options are defined by the kind of major crops, degree of management and land development, and the public land use policies. The cropping pattern and management of the cultivated private land is shaped by the physical characteristics of the land, irrigation availability and local technology. Publicly owned land is used for grazing, forest products or protected forests. However, with the fairly recent initiation of afforestation and rehabilitation of eroded land and the legal arrangement of community forests, some public land is managed to a certain extent. For example, the Panchayat Forests Act of 1978 allows management inputs by the community to the public land on a limited acreage.

Depending upon the nature of cultivation practices and management input, the following land use options are identified:

1. Irrigated terrace cultivation (Khet) - irrigation available (levelled bench terrace, paddy (rice) is the main crop followed by the rotation of some secondary crop).

2. Dry upland terrace cultivation (Bari) - rainfed (gently sloped terrace, corn is the main crop followed by a rotation of some secondary crop).

3. Unmanaged pasture - grass land with almost no management inputs.

4. Unmanaged forest - mixed forest without management inputs (uncontrolled harvest of tree fodder and fuelwood and grazing).

5. Managed Pasture - grass land with some management inputs (fencing, seeding and controlled grazing).

6. Managed forest - mixed forest with some management inputs (fencing, reforestation, and controlled harvesting).

   Managed forest can be developed in two ways - (i) By simply protecting the unmanaged forest from livestock and applying sustained yield management practices. The sustained yield is assumed to be attained approximately after a waiting period of 5 years (Flemming, 1983). (ii) By converting the agricultural, unmanaged pasture and scrub lands into plantation forest protected from livestock and managed for sustained yield. The sustained annual yield is assumed to be attained after 15 years of afforestation (Levenson, 1979). These sustained yield managements respond primarily to fuelwood production.

7. Scrub - mixture of shrubs and stunted trees on abandoned land (still provides some nominal harvest of fodder and fuelwood).

8. Protected forest - forest protected by government or local community for various reasons (wildlife, water resources, cultural values, etc.).

9. Waste land and others - mostly highly denuded (bare surface, roads, villages, streams, etc.).

These land use options are defined specifically for the Phewa-tal watershed based on Fleming's (1983) report and personal knowledge of the hill farming system. Local variations should be considered when this model is applied in general.

Planning Unit : A land use planning unit is defined as the noncontiguous area covered by the current land use in a land class. For example, the area in land class III covered by unmanaged forest constitutes a planning unit. Since there are nine land classes and nine land use options, theoretically 81 (9*9) land planning units are possible in a watershed. Table 3 provides the area in hectares of each land planning unit in Phewa-tal watershed. They form the RHS values

Table 3. No. of land planning units and their area (ha) for Phewa-tal watershed.

Planning unit (l=ik)[a]	Area (ha)	Planning unit (l=ik)[a]	Area (ha)
11	706.0	58	23.0
13	3.0	71	185.0
18	10.0	72	1274.0
21	242.0	73	122.0
31	2117.0	75	524.0
33	212.0	77	95.0
35	65.0	78	564.0
38	86.0	79	17.0
39	9.0	81	56.0
43	86.0	82	719.0
45	21.0	83	254.0
47	10.0	85	494.0
48	106.0	87	184.0
51	526.0	88	2380.0
53	178.0	89	4.0
55	23.0	99	176.0
57	8.0		

a

i= 1,2,...,9 land classes, and k= 1,2,...,9 land use options.

of A_l and I_{lj} for $j = 1$. The values of I_{lqj} for this test problem are the irrigable areas in planning units which have irrigation facilities. It is recommended that the values for I_{lqj} should be realistically assigned for respective periods if future irrigable areas are expected to expand.

Land Use Sequence ; Land use sequences are the identified sequence of planting and harvesting alternatives. These land use alternatives are either a continuation of the current land use or conversion to other alternatives. Altogether, five land use conversion alternatives are considered. They are: (1) Irrigated terrace cultivation, (2) Dry land terrace cultivation, (3) Managed pasture, (4) Managed forest, and (5) Protected forest. There are four land use sequences for each alternative, as conversion can occur in the first four periods. If the current land use is one of these alternatives, then there would be four for each converted land use and one for current land use forming altogether 17 sequences. An example of such a sequence is shown in Table 4. *H* and *P* are the harvesting and planting that occur in the defined period. The subscripts correspond to the land use options. These sequences have been developed by adopting a technique similar to that employed in timber harvest scheduling in Model I (Johnson and Scheurman, 1977). If the exiting land use is one of the following: (1) unmanaged pasture, (2) unmanaged forest, or (3) scrub, then there would be altogether twenty one land use sequences. An example of such a sequence is shown in Table 5.

The land use sequences which convert or continue into irrigated terrace and dry land terrace have planting and harvesting accounted for every planning period. The land use sequences which continue into unmanaged pasture, unmanaged forest and scrub account for only the harvesting every period. The land use sequences which convert or continue land into managed pasture, managed forest and protected forest have planting accounted only in the period of conversion. Harvesting is accounted for every period for the managed pasture, and managed forest converted from unmanaged forest. It is accounted for every third period of conversion onwards when converted from other land uses to managed forest. The protected forest yields no harvest either fuelwood or fodder.

Table 4. Land use sequences for an example planning unit with initial land use of irrigated terrace cultivation.

Land use sequence number	Planning period 1	2	3	4	5
1	H_1P_1	H_1P_1	H_1P_1	H_1P_1	H_1P_1
2	H_1P_1	H_1P_1	H_1P_1	H_1P_2	H_2P_2
3	H_1P_1	H_1P_1	H_1P_2	H_2P_2	H_2P_2
4	H_1P_1	H_1P_2	H_2P_2	H_2P_2	H_2P_2
5	H_1P_2	H_2P_2	H_2P_2	H_2P_2	H_2P_2
6	H_1P_1	H_1P_1	H_1P_1	H_1P_4	H_4 –
7	H_1P_1	H_1P_1	H_1P_4	H_4 –	H_4 –
8	H_1P_1	H_1P_4	H_4 –	H_4 –	H_4 –
9	H_1P_4	H_4 –	H_4 –	H_4 –	H_4 –
10	H_1P_1	H_1P_1	H_1P_1	H_1P_6	– –
11	H_1P_1	H_1P_1	H_1P_6	– –	– –
12	H_1P_1	H_1P_6	– –	– –	H_6 –
13	H_1P_6	– –	– –	H_6 –	H_6 –
14	H_1P_1	H_1P_1	H_1P_1	H_1P_8	– –
15	H_1P_1	H_1P_1	H_1P_8	– –	– –
16	H_1P_1	H_1P_8	– –	– –	– –
17	H_1P_8	– –	– –	– –	– –

Note: (1) *H*- harvesting and *P* - Planting. (2) Subscripts: 1 - Irrigated terrace cultivation, 2 - Dry land terrace cultivation, 4 - Managed pasture, 6 - Managed forest, 8 - Protected forest.

Table 5. Land use sequences for an example planning unit with initial land use of unmanaged forest.

Land use sequence number	Planning period 1	2	3	4	5
1	H_5 –	H_5 –	H_5 –	H_5 –	H_5 –
2	H_5 –	H_5 –	H_5 –	H_5P_1	H_1P_1
3	H_5 –	H_5 –	H_5P_1	H_1P_1	H_1P_1
4	H_5 –	H_5P_1	H_1P_1	H_1P_1	H_1P_1
5	H_5P_1	H_1P_1	H_1P_1	H_1P_1	H_1P_1
6	H_5 –	H_5 –	H_5 –	H_5P_2	H_2P_2
7	H_5 –	H_5 –	H_5P_2	H_2P_2	H_2P_2
8	H_5 –	H_5P_2	H_2P_2	H_2P_2	H_2P_2
9	H_5P_2	H_2P_2	H_2P_2	H_2P_2	H_2P_2
10	H_5 –	H_5 –	H_5 –	H_5P_4	H_4 –
11	H_5 –	H_5 –	H_5P_4	H_4 –	H_4 –
12	H_5 –	H_5P_4	H_4 –	H_4 –	H_4 –
13	H_5P_4	H_4 –	H_4 –	H_4 –	H_4 –
14	H_5 –	H_5 –	H_5 –	H_5P_6	H_6 –
15	H_5 –	H_5 –	H_5P_6	H_6 –	H_6 –
16	H_5 –	H_5P_6	H_6 –	H_6 –	H_6 –
17	H_5P_6	H_6 –	H_6 –	H_6 –	H_6 –
18	H_5 –	H_5 –	H_5 –	H_5P_8	– –
19	H_5 –	H_5 –	H_5P_8	– –	– –
20	H_5 –	H_5P_8	– –	– –	– –
21	H_5P_8	– –	– –	– –	– –

Note: (1) *H*- harvesting and *P* - Planting. (2) Subscripts: 1 - Irrigated terrace cultivation, 2 - Dry land terrace cultivation, 4 - Managed pasture, 5 - unmanaged forest, 6 - Managed forest, 8 - Protected forest.

Constraint coefficients: Each land class and land use option combination produces certain yields of food grain, fodder and fuelwood depending upon the level of input and management practices. In the absence of scientific estimates of the yields of major crops by land classes they will be computed based upon published data, personal observation, informal surveys, and interpolation of data. Production activities such as orchards, vegetables etc. are ignored because of their negligible effect on land use decisions.

The constraint coefficients $FOOD_{lqj}$, are the equivalent rice production per hectare in planning unit l, land use sequence q and planning period j. They are computed by converting the various annual food grain yields into equivalent calorie content. This conversion allows the treatment of all grains such as rice, wheat, corn etc. in a common scale. Appendix I shows the method of computing these values. The values of $FOOD_{lqj}$ for input into the model are five year aggregates, computed by multiplying the annual average value five times.

Technical progress at the rate of 10 percent per planning period is assumed. This is accounted for making the coefficient value of a period 10 percent larger than that of the previous period. Table 6 presents the extrapolated annual rice equivalent food grain yields for various land classes and planning periods.

The constraint coefficients $FODD_{lqj}$, are the periodic yield of total digestible nutrients of the fodder for planning unit l, land use sequence q and the harvest occurring in planning period j. The "fodder" represents the overall livestock feed supplied through sources such as straw and residue from cereal crops, forage from pastures and fodder from trees and shrubs. Appendix II shows the derivation for the annual yield values. The values of $FODD_{lqj}$ for the model input are computed by multiplying the annual values by five. It is assumed that the impact of technical progress is insignificant for fodder production and equals zero. Table 7 presents the extrapolated annual fodder yields for various land classes.

Table 6. Extrapolated annual rice equivalent food grain yields (kgs/ha) for various land classes.

Land class	Planning periods				
	1	2	3	4	5
Irrigated terrace					
I	2226.8	2449.5	2694.4	2963.9	3260.3
II	2023.0	2225.3	2447.8	2692.6	2961.8
III	1820.7	2002.8	2203.0	2423.4	2665.6
IV	1638.6	1802.5	1982.7	2180.9	2399.0
V	1474.7	1622.2	1784.0	1962.8	2159.1
VI	1327.3	1469.0	1606.0	1766.6	1943.3
VII	1194.6	1314.0	1445.5	1590.0	1749.0
VIII	1075.1	1182.6	1300.8	1430.9	1574.0
Dry land terrace					
I	2062.8	2269.1	2495.9	2745.6	3020.1
II	1907.6	2098.3	2308.2	2539.0	2792.9
III	1716.8	1888.5	2077.3	2285.1	2513.6
IV	1545.2	1699.7	1869.7	2056.7	2262.2
V	1390.6	1529.7	1682.6	1850.8	2035.9
VI	1251.6	1376.8	1514.4	1665.8	1832.5
VII	1126.4	1239.0	1362.9	1499.2	1649.2
VIII	1013.8	1115.2	1226.7	1349.4	1484.3

Source : Appendix I.

Table 7. Extrapolated annual fodder yields (TDN kgs/ha) for various land classes.

Land class	Irrigated terrace	Dry land terrace	Unmanaged pasture	Unmanaged forest
I	1184.1	772.5	217.0	636.6
II	1065.7	696.2	197.3	578.7
III	959.1	626.5	179.3	526.1
IV	863.2	563.9	163.0	478.3
V	776.9	507.5	148.2	434.8
VI	699.2	456.7	133.4	391.3
VII	629.3	411.0	120.0	352.2
VIII	566.4	376.0	108.0	317.0

Land class	scrub	Managed pasture	Managed forest
I	408.8	1084.9	1061.1
II	371.6	986.3	964.6
III	337.8	896.6	876.9
IV	307.1	815.1	797.2
V	279.2	741.0	724.7
VI	251.3	666.9	652.2
VII	226.2	600.2	587.0
VIII	203.5	540.2	528.3

Source : Appendix II.

The coefficients $FUEL_{lqj}$ are the periodic fuelwood yield for planning unit *l*, and land use sequence *q* for the period, when harvest occurs. They are derived from the best available yield estimates for various land uses in the watershed. Appendix III shows the derivation of the annual values, which are then multiplied by five to compute the periodic values. Technical progress is zero. Table 8 presents the extrapolated annual fuelwood yield for various land classes and planning periods.

The coefficients $SOIL_{lqj}$, are the periodic soil loss per hectare for planning unit *l*, and land use sequence *q*. They are the predicted soil loss for each land class and land use combination for the respective periods of the land use. The technique applied to predict soil loss is the Universal Soil Loss Equation (Wischmeir and Smith, 1965). The equation is composed of the variables: rainfall (rainfall erosivity), soil characteristics (soil erodibility), topographic factors (length of slope and slope gradient); vegetative cover and management (cropping management factor) and mechanical manipulation of the surface (conservation practice). For a specific site, the first three variables are constant. By varying the cropping management and conservation practices (mainly bench terracing), the soil loss from the site can be varied. In that sense, they are the controllable variables.

Each land use option can be defined to have a particular cropping management factor value for the specific planning period if the rotation expands for more than a single period. Shakya (1982) estimated the values of the variables for the equation and verified the predicted soil loss by comparing the measured values. The estimated values of all the variables are valid for this study. But the estimates for cropping management factors for managed forest were only for the established condition. Additional cropping management factors need to be estimated to consider the periodic differences in vegetative cover of the newly planted forest. Appendix IV provides a tabular summary of these values.

The coefficients $COST_{lqj}$, are the periodic cost for planning unit *l* and land use sequence *q*. The only official estimates available are the cost of production of various crops (Agricultural Sta-

Table 8. Extrapolated annual fuelwood yield (cu. m/ha) for various land classes.

Land class	Unmanaged forest	Scrub	Managed forest
I	17.6	5.9	29.3
II	16.0	5.3	26.6
III	14.5	4.8	24.2
IV	13.2	4.4	22.0
V	12.0	4.0	20.0
VI	10.8	3.6	18.0
VII	9.7	3.2	16.2
VIII	8.7	2.9	14.6

Source : Appendix III.

tistics of Nepal, 1983). Since they do not explain how the costs are derived, estimates for cost of crop production and land use conversion such as terrace construction, afforestation, and establishment of managed pasture are estimated separately. Appendix V presents the values of various cost components. The periodic cost coefficients are computed by multiplying the annual cost by five and adding the construction and establishment cost, if any to them. For the crops with rotation expanding over more than a planning period such as managed forest, the periodic cost coefficients are the afforestation cost that occurs in the respective period.

First Period Achievement Levels and Composite Function Denominators : The first period achievement levels are computed by multiplying the area of each planning unit by periodic constraint coefficients for the current land use. These values are then eventually tied to periodic constraints through the selected values of α, β, γ, θ and τ. The values of the denominators of the composite function are computed by multiplying the values of first period achievement level by the number of planning periods.

Chapter IV

RESULTS AND INTERPRETATION

The model was run with the data from Phewa-tal watershed. Phewa-tal watershed is located in the Kaski District of the Western Develpment region. The waterhed has an area of 113 square kilometers and contains one of Nepal's most prominent lakes, Phewa-tal. An analysis of the slope categories shows that 60 percent of the watershed has slopes between 20 and 60 percent, with an average slope of 40 percent (Fleming, 1983). About 10 percent of the watershed is flat to rolling (0 to 10 percent slope), and 15 percent is very steep (60 to 100 percent slope). The total population in the watershed is 33,609 and the total number of households is 6015 (IWMP, 1980).

This chapter presents the results and their interpretation for selected runs of the model. First, a projected land use trend without any planning effort will be presented. This is a baseline analysis for comparision with the land use plans generated by the model. Second, land use plans under single objective functions will be presented to evaluate the impact of different ranking of objectives. Third, land use plans under various relative importance weights will be discussed. Fourth, general observations of the model behavior will be interpreted. And finally, an example land use plan will be presented and project design and policy implications of such plan will be discussed.

Projected Land Use Trend Without Planning

Fleming (1983) projected the land use trend from 1978 to 1998 with 1978 growth rates and no management plans for the Phewa-tal watershed (Table 9). The following assumptions were made for this projection:

- Agricultural productivity per hectare will not increase, and , hence, cultivated terrace land must increase to match a population growth rate of 2 percent per year.
- Animal population will increase at the same rate as the human population, and, therefore, grazing land will increase 2 percent per year.
- Scrub land will increase 2 percent per year from the depletion of forest for fuelwood extraction.
- Forest land will eventually decrease to supply the demand for other land uses.

As the numbers of people and animals increase, land is converted from forest to other uses. Land use progresses from forest to scrub to grazing land to cultivated terrace. At the assumed rate of land use with no management planning, forest land is likely to disappear by 1998.

The projected land use trends specify only the area (hectares) in various land uses. They do not project changes by land classes. Hence, it is not possible to make quantitative estimates of the land use products, soil loss and costs. However, some speculations can be made as follows:

1. Although land in agricultural use will increase, the land use conversion to cultivated land will occur on poorer land classes. Better lands are already been in agricultural use. This

Table 9. Projected land use (in percent of total area)1978-98, in the Phewa-tal watershed, with 1978 growth rates and no management plan.

Land	Index year				
use	1978	1983	1988	1993	1998
Cultivation	51.96	57.24	63.03	69.42	75.64
Grazing	12.41	13.60	14.90	16.34	17.92
Scrub	9.17	10.10	11.12	12.24	5.60
Forest	26.45	19.06	10.93	2.00	0.00

Note: The figures are computed from data projected by Fleming (1983).

implies that the increase in food production will occur at a decreasing rate and is likely to be more than the annual growth of cultivated land by 2 percent.

2. Forest land will decrease and eventually will disappear completely by 1998. Decrease in forested areas will make the fuelwood shortage more and more critical. The slightly increasing trend in scrub land will not be able to alleviate the fuelwood shortage. Fuelwood yield from scrub land is only one third that of forest land, hence decrease in fuelwood production will not be compensated for by increases in scrub land.

3. Grazing land will increase. This will increase fodder production. Fodder production will also increase because of increased cultivated and scrub land. However, decreased forest land will decrease the fodder.

4. Grazing and scrub land are the most vulnerable to soil erosion. Increase in the land proportion in these uses will automatically increase the soil erosion, which will reduce the productive capacity of the land on site and result in downstream lake sedimentation. The lake sedimentation reduces the life of hydro-electricity and irrigation installations.

In general, food and fodder production will have to increase to meet the demand of the increasing human and livestock population to maintain the present living standards. This will involve converting the forest land into cultivated terrace, grazing, and scrub lands. The consequences will be a critical shortage of fuelwood. Soil erosion will increase.

In absence of land use plans and development efforts, the projected trend is probable. Despite the government efforts at limiting the population growth rate, an increase in population is inevitable for the foreseeable planning horizon. Increase in human and livestock population will put immediate pressure on food and fodder production. The food and fodder production will receive higher weight for land allocation. Forest conservation will receive lower weight, because the impact of forest depletion is felt only in the long run, it is common property, and land use control is ineffective. This eventually may lead to the complete disappearance of forest.

Development projects should be designed to implement the land use plans in light of this probable land use trend. Land use planning should be the basis for prescribing policies, designing development projects, and administering the management of land. Legislative tools such as Panchayat Forest Act (1982) should be interpreted as an effective means to overcome the problem of common property management. The act decentralizes the responsibility for the control over vulnerable public lands to the local people. The act seeks to provide incentives for local people to manage and control land use. Successful attempts have been made in organizing local people's participation in the planning and implementation processes (Leuschner and Shakya, 1986).

Land Use Plans Under Single Objective Functions

The model can be run as a single objective programming problem. This is done by assigning the concerned objective's relative importance weight the value of 1 and the other ratios the value of 0. Single objective function problems were run for two sets of periodic achievement growth rates ($\alpha, \beta, \gamma, \theta$ and τ). Periodic growth rate constraints were set loose for one ($\alpha = \beta = \gamma = \theta = \tau = 0$), and tight for another ($\alpha = \beta = \gamma = \theta = 0.1$ and $\tau = 0$). These runs were made to compare the extreme ranges of the achievement levels of the objective functions for the defined periodic growth rate policy constraints.

One important assumption in the model is that technological progress in the agriculture sector is expected through development projects. Hence, it was assumed in all the runs that the technical progress would increase the food grain yield by 10 percent per planning period. This rate of technological progress can be considered probable in the light of the present trends of development in the agricultural sector. Due to complexity and the lack of data, the impact of soil erosion on the decrease of yield per hectare could not be considered.

First set: The first set had nondecreasing periodic achievement level constraints for food, fodder, and fuelwood and nonincreasing for soil loss and cost. The first period constraint levels were set at the current levels. For the zero values of the parameters α, β, γ, θ and τ periodic constraint levels are same as the first period constraint levels.: Table 10 presents the annual achievement levels of food, fodder and fuelwood production, soil loss and costs for the respective planning periods for the first set of runs. The achievement levels exceed the lower bound constraint levels for food, fodder and fuelwood in some periods. They are interpreted as excess production. When the achievement levels fall below the upper bound constraint levels for soil loss and cost, they are the savings.

Annual food production increased at periodic rates of 9.2, 11.4, 11.3 and 10.5 percent when maximized (first run). Fodder production increased at rates of 0.5, 2, 3, and 3 percent. Fuelwood production was maintained at the first level throughout the planning horizon except for a slight increase in the fourth period. The soil loss was slightly reduced in subsequent periods from the first level. The cost remained almost same with a slight reduction in the fifth period.

Fodder production increased at the rate of 16, 5, 1, and 0 percent when maximized (second run). Annual food production remained at the first level for the first three periods and a slight increase occurred in fourth and fifth period. Fuelwood production slightly increased in the second period. Soil erosion and costs decreased significantly as the planning periods advanced.

Fuelwood production increased at the rate of 51, 0, 123 and 52 percent for subsequent periods from second period onwards when maximized (third run). Annual food production increased slightly in the third, fourth and fifth period compared to the first level. Fodder production re-

Table 10. Periodic annual achievemets for single objective function for $\alpha = \beta = \gamma = \theta = \tau = 0$

Planning Period	Food tons rice equivalent	Fodder tons TDN[a]	Fuel m^3	Soil loss tons	Cost Rs.'000/-
λ_a = 1 (food production maximization)					
I	9461	5225	11818	335873	27544
II	10336	5253	11818	330668	27544
III	11519	5334	11818	329581	27544
IV	12831	5383	13678	330650	27544
V	14178	5392	11818	328582	27383
λ_b = 1 (fodder production maximization)					
I	9461	5225	11818	335873	27544
II	9461	6057	13444	272056	23874
III	9461	6364	11818	85650	19816
IV	9714	6451	11818	138929	18825
V	10685	6451	11818	59643	18825
λ_c = 1 (fuel production maximization)					
I	9461	5225	11818	335873	27544
II	9461	5225	17827	315357	26725
III	9881	5225	17827	217122	20701
IV	9874	5225	39794	91758	18231
V	10251	5544	60645	57482	17907
λ_d = 1 (soil loss minimization)					
I	9461	5225	11818	335873	27544
II	9461	5542	11926	180041	26326
III	9461	5993	11818	97177	22690
IV	9461	6052	11818	47585	18526
V	9461	5347	11900	46686	18178
λ_e = 1 (cost minimization)					
I	9461	5225	11818	335873	25843
II	9461	5482	11818	320070	21699
III	9461	5662	13498	308057	18670
IV	9461	6757	11818	308007	16343
V	9461	5225	11818	302320	15544

[a] Total digestible nutrients.

mained almost constant with a small increase in the fifth period. Significant decreases in soil erosion and slight decreases in cost occurred.

Soil loss decreased drastically when minimized (fourth run). Food production remained constant. Fodder increased slightly. Fuelwood also increased slightly in the second and fifth period. The costs also decreased significantly. Soil loss per hectare is lowest in managed pasture. Therefore, all the available lands were allocated to managed pasture after meeting the periodic constraints on food, fodder and fuelwood achievements.

Costs reduced significantly when minimized (fifth run). Food production remained constant. Fodder production slightly increased for the second, third and fourth periods. Fuelwood production remained constant with a slight increase in the third period. The soil loss reduction was not significant. Minimum land use changes occurred in this run compared to others above. This is obvious for the costs are being saved through minimizing the land use conversion and establishment costs.

The results above show that different land use plans and periodic achievement levels occur when each objective is optimized. This indicates that the ranking of the objective functions has a significant impact on the land use plans. The achievement levels also indicate the extreme possible achievements, given the problem's structure.

Second set: The second set of the problems had periodic achievement level constraints for food, fodder and fuelwood set at increasing more than or equal to 10 percent from the previous period. The periodic cost constraints were allowed to increase by 10 percent or less from the previous period. The periodic soil loss constraints were nonincreasing.: These runs became infeasible. It was not possible to maintain 10 percent periodic growth rates of food and fodder when the first period constraint levels were set at the current level of production. To get feasible solutions, either the growth rate parameters should be changed (lowered) or the first period constraint levels must be artificially changed. Deficit in production can be estimated when achievement levels are changed. This would imply that the project could import the deficit amount of food and fodder production. Deficits in food from the planned achievement level occurs because some of the cultivated land will be allocated to other uses such as pasture or forest. This is shown by an illustrative example to be discussed later.

Subsequent runs were made by setting the first period constraint levels at their highest feasible values. These values were determined from the computer outputs of the previous infeasible solutions. The results of all five runs produced the same plan, which means there is only one unique optimal plan for the defined growth rates of periodic achievements. The assigned periodic constraint levels are so close to all single objective optimal solutions that changes in the plan are not possible without relaxing the growth rates. Table 11 presents the results of a run (all 5 runs). The food, fodder and fuelwood productions increase at least 10 percent per period from the assigned first period constraint levels.

Since the first period constraint levels of food and fodder production were assigned at lower than the current levels, there will be some deficits compared to the periodic production that would have occurred with current levels and at the defined growth rates. When calculated separately the food production deficits are approximately 5 percent per period (i.e., 1 percent per year). This can be interpreted as the deficits from the desired achievement levels and periodic growth rates. Periodic deficits for fodder production are about 14, 20, 20 and 20 percent, respectively, the second period onwards. Fuelwood production increased at the rate of 10 percent per period with surplus production in fourth and fifth periods. Soil loss is reduced as the periods advance. Costs increased at the rate of 10 percent for the second period and decreased from third period onwards.

These results show that the individual objective functions do not produce different land use plans and periodic achievement levels when the periodic flow policy parameters impose tight constraints. Therefore, these policy parameters should be carefully evaluated before assigning them.

Table 11. Periodic annual achievements for single objective functions for $\alpha = \beta = \gamma = \theta = 0.1$, and $\tau = 0$.

Planning Periods	Food tons rice equivalent	Fodder tons TDN	Fuel m^3	Soil loss tons	Cost Rs.'000/-
I	9461	5224	11818	335873	27544
	(9000)[a]	(4266)	(11818)	(335873)	(27544)
II	9900	5002	13000	310983	30298
	(9900)	(4693)	(13000)	(310983)	(30298)
III	10890	5162	14300	250502	25043
	(10890)	(5162)	(14300)	(250502)	(33328)
IV	11979	5679	27491	154986	24963
	(11979)	(5679)	(15730)	(250502)	(36661)
V	13176	6247	44185	73685	24807
	(13176)	(6247)	(17304)	(250502)	(40327)

[a] Values in parenthesis are lower bound constraint levels for food, fodder and fuelwood and upper bound for soil loss and cost.

Land Use Plans Under Various Relative Importance Weights

Two sets of problems were run for the relative importance weight structures listed in Table 2 in chapter 3. Recall there were 10 weight combinations. These weights correspond to the arbitrarily chosen ranking and preference relation. The achievement level policy differs by set. The first set is the the same as the Table 10 policy ($\alpha = \beta = \gamma = \theta = \tau = 0$). The second set is the same as Table 11 policy ($\alpha = \beta = \gamma = \theta = 0.1$; $\tau = 0$). Both sets of run assumed 10 percent periodic growth rates.

The first set of runs showed only small differences for the various weight structures. Table 12 presents the achievement levels for the three most diverse weight structures. Changing relative importance weights does not cause much change in the achievement level.

The results for the second set of runs showed no difference at all for the various weight structures. This was obvious from the results of the single objective functions (Table 11). When the variation in ranking does not show any impact, the variation in weight structures within a particular ranking becomes obviously ineffective.

General Observations

As discussed above there are two approaches of generating land use plans. One approach uses loose periodic constraints. In this approach the plans are evaluated by matching the model generated periodic achievement levels with the desired levels. Another approach sets periodic constraints equal to the desired growth rates. This approach generates fewer alternative plans compared to the first approach.

Variation in ranking, preference relations and relative importance weights plays a significant role in generating alternative land use plans in the first approach. They may not play much

Table 12. Planning horizon total and periodic annual achievements with $\alpha = \beta = \gamma = \theta = \tau = 0$ for selected weights

Planning Periods	Food tons rice equivalent	Fodder tons TDN	fuelwood m^3	Soil loss tons	Cost Rs.'000/-
$\lambda_a = 5/19$, $\lambda_b = \lambda_c = 4/19$, $\lambda_d = \lambda_e = 3/19$					
I	9461	5225	11818	335873	27544
II	9461	5225	17827	301290	26097
III	9841	5225	17827	186894	20632
IV	9841	6091	39421	74686	19111
V	10825	6091	60606	59661	19074
25 yrs. total	247150	139295	737505	4792030	562290
$\lambda_a = 5/11$, $\lambda_b = \lambda_c = 2/11$, $\lambda_d = \lambda_e = 1/11$					
I	9461	5225	11818	335873	27544
II	9461	5225	17827	301435	27544
III	10329	5225	17827	199390	22390
IV	10382	6027	39328	78370	20685
V	11420	6027	58835	58760	20648
25 yrs. total	255225	138650	728285	4869150	594055
I	9461	5225	11818	335873	27544
II	9461	5225	17827	315767	26365
III	9882	5225	17827	181920	20759
IV	9899	6092	39426	71495	19250
V	10890	6092	60634	58888	19214
25 yrs. total	247975	139305	737675	4819725	565670

significant role in the second approach if the periodic growth rate policy parameters impose tight constraints. They may also cause more infeasible solutions. However, in infeasible cases, first period constraint levels can be artificaially manipulated to get feasible solutions. This implies that the project imports deficit achievements of the respective objectives.

Therefore, tightness of the periodic constraints is important. The tighter the periodic constraints, the fewer diverse land use plans are generated. More flexible periodic constraints generate more diverse land use plans. The decision makers are more likely to find an acceptable plan where there are more alternative plans to choose from. Thus, loose constraints are generally recommended.

An example Land Use Plan and Project Design Implications

The project design implication of a land use plan prescribed by the model is explained by analyzing an example solution. An example is chosen with growth rate parameters comparable to the assumptions made by Fleming (1983) in projecting land use trends with no planning (Table 1). This provides the common basis for a comparative study of land use with and without planning. Table 13 presents the list of decision variables and hectares commanded by each variable for the optimal solution. This corresponds to the periodic growth rate parameters of $\alpha = \beta = \gamma = \theta = 0.1$, and $\tau = 0$.

A periodic land use plan can be developed (Table 14) by tracing back the decision variables' numerical code. Table 15 presents the overall periodic land use for the watershed. Table 15 can be compared with the land use trend for the watershed without planning (Table 9). Since the input data used in this model were estimated at the time of Fleming's (1983) work the planning periods can be assumed to approximately coincide with the index years.

Table 13. Land use plan for $\alpha = \beta = \gamma = \theta =$ 1.1, $\tau = 0$ and selected weights[a]

Land use sequence[b]	Hectares	Land use sequence	Hectares
X111	706	X713	145
X139	3	x723	145
X211	242	X726	3
X311	2117	X7212	390
X338	80	X7213	736
X339	132	X7316	122
X358	65	X7516	342
X411	178	X7517	182
X414	21	X778	95
X438	86	X813	56
X454	21	X821	663
X478	10	X823	56
X511	526	X8312	225
X5316	62	X8316	24
X5317	116	X858	4
X558	23	X8512	92
X5716	8	X8516	398
X711	40	X8716	194

[a] $\lambda_a = 5/11, \lambda_b = \lambda_c = 2/11, \lambda_d = \lambda_e = 1/11.$

[b] Numerical code for land use sequence : Xijk, where i = 1,2,...,9 land classes; j = 1,2,...,9 land use options; and k = 1,2,...,17 for j = 1,2,4,6,8 and k = 1,2,...,21 for j = 3,5,7. k is the code for land use conversion period and converted land use. Land use options code: 1 - irrigated terrace, 2 - dry land terrace, 3 - unmanaged pasture, 4 - managed pasture, 5 - unmanaged forest, 6 - managed forest, 7 - scrub, 8 - protected forest, 9 - Waste land. See Tables 2 and 3 chapter III for key to the land use conversion code.

Table 14. Periodic land use conversion plan for the example solution.

Land class/ Land use	Continue (CT)/ Converted (CV)	Hectares in Planning period				
		I	II	III	IV	V
Land class I						
1	CT	706	706	706	706	706
3	CT	3	-	-	-	-
2	CV from 3	-	3	3	3	3
Land class II						
1	CT	242	242	242	242	242
Land class III						
1	CT	2117	2117	2117	2117	2117
3	CT	212	80	-	-	-
2	CV from 3	-	132	212	212	212
5	CT	65	65	-	-	-
2	CV from 5	-	-	65	65	65
Land class IV						
1	CT	199	199	199	199	199
3	CT	86	86	-	-	-
2	CV from 3	-	-	86	86	86
5	CT	21	21	-	-	-
2	CV from 5	-	-	21	21	21
7	CT	10	10	-	-	-
2	CV from 7	-	-	10	10	10
Land class V						
1	CT	526	526	526	526	526
3	CT	178	62	-	-	-
6	CV from 3	-	116	178	178	178
5	CT	23	23	-	-	-
2	CV from 5	-	-	23	23	23
7	CT	8	8	-	-	-
6	CV from 7	-	-	8	8	8

(continued to next page)

Table 14. continued.

Land class/ Land use	Continue (CT)/ Converted (CV)	Planning period				
		I	II	III	IV	V
Land class VII						
1	CT	185	185	185	185	185
2	CT	1274	538	145	145	145
4	CV from 2	-	-	3	3	3
6	CV from 2	-	736	1126	1126	1126
5	CT	524	342	-	-	-
6	CV from 5	-	182	524	524	524
7	CT	95	95	95	-	-
2	CV from 7	-	-	-	95	95
Land class VIII						
1	CT	56	56	56	56	56
2	CT	719	719	719	719	719
3	CT	249	249	-	-	-
4	CV from 3	-	-	225	225	225
6	CV from 3	-	-	24	24	24
5	CT	494	494	-	-	-
2	CV form 5	-	-	4	4	4
4	CV from 5	-	-	92	92	92
6	CV from 5	-	-	398	398	398
7	CT	194	194	-	-	-
6	CV from 7	-	-	194	194	194

Note: Numerical code for land use options - 1 - irrigated terrace, 2 - dry land terrace, 3 - unmanaged pasture, 4 - managed pasture, 5 - unmanaged forest, 6 - managed forest, 7 - scrub, 8 - protected forest, 9 - Waste land. See Tables 2 and 3 chapter III for key to the land use conversion code.

Table 15. Periodic land use (hactares) for the example solution.

Land use	Planning period				
	I	II	III	IV	V
Irrigated terrace	4031	4031	4031	4031	4031
Dryland Terrace	1993	1392	1288	1383	1383
Cultivation	6024	5423	5319	5414	5414
(Percent)	(52.10)	(46.90)	(46.00)	(46.00)	(46.00)
Unmanaged Pasture	728	477	-	-	-
Managed Pasture	-	-	320	320	320
Grazing	728	477	320	320	320
(Percent)	(6.29)	(4.12)	(2.76)	(2.76)	(2.76)
Scrub land	307	307	95	-	-
(Percent)	(2.65)	(2.65)	(.82)		
Unmanaged Forest	1127	945	-	-	-
Managed Forest	-	1034	2452	2452	2452
Protected land	3169	3169	3169	3169	3169
Forest	4296	5148	5621	5621	5621
(Percent)	(37.15)	(44.52)	(48.62)	(48.62)	(48.62)
Waste land	206	206	206	206	206
(Percent)	(1.78)	(1.78)	(1.78)	(1.78)	(1.78)

From Table 15 it is evident that forest and scrub land retain almost 50 percent of the land in future periods, whereas the forest land almost disappears in the unplanned trend. Lands are converted from dry land terrace, unmanaged pasture, unmanaged forest and scrub to managed pasture, managed forest and protected forests.

Each plan should be interpreted for project design, policy implications and strategy formulation in a Nepalese Hill development context. Table 11 has earlier presented the periodic achievement levels of various objectives for the Table 15 plan. Food must be imported at approximately 5 percent per period to maintain the current level of food consumption at the policy determined growth rates (10 percent per period). The fodder deficit is critical suggesting the need to decrease the livestock population, or import fodder substitutes. Decreasing the livestock population could be possible, because the livestock population needed to support the manure and draft requirements may not increase since the land under agricultural use actually decreases. Soil erosion is reduced in the subsequent periods. This will maintain the site productivity and reduce the downstream damages. Reductions in cost occur while food increases. This would free resources for other uses.

Chapter V

DISCUSSION

The objective of this research study was to develop a land use planning model for designing long term land use plans for subsistence farming systems in the Nepalese Hill region. This has been accomplished with a multiobjective programming model. The overall contribution of this study lies in presenting the identified problem in mathematical form and deriving solutions to the defined objectives. The model is formulated with particular emphasis on a decision making environment of developing countries.

Presenting such a model is a daring task. It involves gross assumptions about the problem environment and rationalizations of decision maker's behavior. It involves simplifying the complex nature of the problem. The strength and weakness of such a model depends upon the appropriateness of the assumptions and rationales. It also depends upon the practicality of the model for field implementation.

Therefore, this chapter includes discussions specifically on assumptions, rationales and practicality of the model. In general, the issues are discussed to caution the reader about potential pitfalls when applying and implementing the model on other project areas.

Assumptions of the problem environment

The problem environment includes all aspects of nonprice economy, the farming systems and technological progress. Discussions will address economic efficiency, broadening the capacity of the model through improvements in defining planning units, land use sequences, and constraints, and estimating the technological coefficients. The organisational context of the model application will also be discussed.

Nonprice economy : The model is built upon the assumption that no price driven market economy exists to influence the land use decision. But some land use products may be influenced by the market accessibility and trade potential. For example, food grain can be exported out of the watershed to nearby markets. In the Nepalese Hills, farmers often sell clarified butter (ghee) in a limited quantity to nearby markets to buy essential goods, not produced locally.

Despite the erroneous assumption of a totally nonprice economy, the model is valid in many watersheds. There are only a few farms big enough to sell their products beyond family consumption. And, flow of consumption goods in and out of the watershed consists of a very small proportion of the total consumption-production activities. My subjective estimate of the percent of production exchanged for cash is below 15 for a watershed half a day's walk off roads or from major city. A drastic change in this situation cannot be expected from the present trend of the country's economy.

In future, situations may arise where surplus production is possible. In such situations, either the modeling will have to be changed or marketing will have to be made feasible.

Farming systems : The model assumes subsistence farming will remain unchanged throughout the planning horizon. This gives the impression that the model perpetuates a subsistence economy. The planning horizon of 25 years is a significant time span and market accessibility may change. With the development of markets comes the concept of cash crops to replace the crops in the subsistence farming system. In such a scenario, the presently conceived model would need to be modified.

Economic efficiency : A plan is economically efficient, when it meets the combined criteria of technical efficiency and price efficiency (Yotopoulos and Nugent, 1976). The model is capable of producing technically efficient plans. Technically efficient plans mean nondominated solutions in the feasible region. The plan generated by the model currently is not price efficient. Price efficiency means considering various factors such as price, interest rates, inflation rate, subsidies etc. in an optimization problem. In situations, where a price driven market economy influences land use decisions significantly, the model needs to be modified to consider price efficiency as well.

Several modifications can be made to make the model use price information. The crucial factor is how accurately the prices of the land use products can be projected for various periods of the planning horizon. Prices of some products such as food grains may be directly projected through forecasting techniques. But, prices of products such as fuelwood and fodder will be very difficult to project. Cash prices are unlikely to develop for fuelwood and fodder because of their low value. Shadow prices will be needed. But it will be much more complex to predict future shadow prices. If prices can be projected satisfactorily, the model can be modified by converting the three objective functions into a single revenue function. The periodic constraints on these products can also be projected as periodic demands for the products.

Multiobjectives still remain useful because some model outputs, such as soil loss, cannot be given a value. Weights on the revenue, cost and soil loss will still be important considerations to analyse their trade offs.

Technological progress : Technological progress in various fields has a definite impact on land use plans. The demonstration problem has assumed technological progress to effect only in the agricultural sector at the rate of 10 percent per period increase in yield. It is incorporated in the estimation of yields for respective periods. Progress in the agriculture sector is very crucial for retaining forest land in the watershed and curtailing the soil erosion. This is true with the technological progress in forestry and range management as well, so far it relates to increased yields of fuelwood and fodder.

There could be an indirect effect of technical progress on the land use plans. Substitutes and complements to fuelwood and fodder can have important impacts. The model will have to incorporate them if such technological progress develops them.

Planning unit : A planning unit is defined using the land classification system. The land classification system used for the Phewa-tal watershed is not adequate. A better land classification system needs to be developed which has the ability to predict crop yields more precisely.: Land classification is a very basic component of the model and can have significant impact on the quality of the plans. But, the most that could be said about this at present, is that, there is a need for research works in this field. The appropriate direction for such research would be finding better relations between site yield and site factors.

All lands in a class under the current land use and a land use sequence form a planning unit. This makes the decision variables noncontiguous. It does not differentiate the lands in a planning unit by their location. It may be important to break down the planning unit by locations. In this case, a bigger model will be needed. It may even be more meaningful to define the planning units as integer variables. Integer variables would avoid the problem of land use changes on areas of small fractions. This would require modifying the model into a mixed integer programming model.

Land use sequence : Only a selected number of land use sequences were identified. The number of land use sequences is determined by the number of land use options and feasible management regimes under each land use option. The land use options identified are what prevail at present. Several attractive land use options such as agro-forestry operations could be included and the number of land use options could be enlarged.

Land use sequences allow either a continuation of the current land use throughout the planning horizon or the conversion to other land use only once in any period and continuing there onwards. For example, if unmanaged forest is converted to, say, managed forest, it would remain in managed forest throughout the planning horizon after conversion. It need not necessarily be so.

The management regimes considered in forestry are only planting and harvesting on a sustained yield basis. The harvesting takes place when the stand attains maximum mean annual increment. The number of alternative land use sequences could be increased by considering all possible land use options, land use conversions and management regimes.

Technology coefficients : The quality of the plan depends upon the quality of input data. The quality of data on yield estimation is very poor at present. This is because very little study has been done in Nepal on yield estimation. Also, there is almost no study of soil loss prediction in the Nepalese climate, topography and vegetation. Hence, more research is recommended to improve the quality of input data.

Periodic constraints : The parameter values for the periodic constraints are exogeneously determined. They are often subjective values based upon the expectation and confidence of the decision makers on many factors, demand trends for the land use products, policy commitment for soil loss restriction and input resources. These are influenced by population growth rate, employment opportunities, availability and affordability of substitutes, etc.

These constraints can be used in two ways. One way is to make these constraints loose and more emphasis is given in studying the impact of variation in relative importance weights. Another way is to study the various policy implications by changing the parameter values. This is equivalent to using the model as a parametric programming model.

Only two sets of periodic growth rates were assigned in the example problems illustrated earlier. It might have been better to run the model to analyse several other scenarios by parametrically varying the periodic growth rates. One important analysis might have been for a scenario with decreasing rate of periodic soil loss. Currently the rate of soil loss in the watershed is quite high. Reduction in the rate of soil loss should be strongly reflected in the policy parameters.

Organisational context : The selection of the best plan depends upon who the DMs are and what the process of their participation is. Several experiences (Leuschner and Shakya, 1986 and TWP, 1983) provide the basis for defining an organisational structure of identifying the DMs and their participation process. An appropriate organisational set up should be a watershed level planning committee. The members of the committee should act as the DMs. The members, in general, should be composed of local representatives of the government agencies responsible for various components of the project implementation, the people's representatives and the representatives of the donor agencies in case of external funding. The people's representatives might include elected village and watershed level officials. In Nepal, these could be Pradhan Panchas and members of the District Panchayat.

The committee members should be trained to be able to assume DM's responsibilities. Prior to the actual decision making an extensive workshop on the various aspects of the land use planning with the proposed model should be held. This workshop should be helpful for their effective paticipation.

Rationales of Decision Maker's Behavior

Rationales of decision maker's behavior will be discussed in light of the composite objective function. Discussions will explain the characteristics of relative importance weight, ranking, and preference relations, procedures and sensitivity of weights.

Relative importance weight : Relative importance weights are generated by normalizing the discrete weights assigned to each ratio component of the composite objective function. The discrete values range from 1 to 5. 1 and 5 need not necessarily be the lowest and highest values for all sets. Depending upon how flexible the preference relations are, various possible values can be assigned within the condition of the selected preference relation.

After normalizing the discrete weights, the relative importance weights express the importance of each ratio in terms of percentage. For example, after normalizing the discrete weights, set $W_a = 5, W_b = W_c = 4, W_d = W_e = 2$ gets translated into the relative importance weights set $\lambda_a = 0.2941, \lambda_b = \lambda_c = 0.2353$ and $\lambda_d = \lambda_e = 0.1176$. These weights imply increase in the achievement level of objective *a* is 29.41 percent important, whereas increase or decrease in the achievement levels of objectives *b* and *c*, and *d* and *e* are 23.53 and 11.76 percent important respectively.

Two aspects of the proposed relative importance weights must be considered. They are - (1) Are they intuitively appealing to the decision maker, and (2) Are they adequate ?.

They seem to be intuitively appealing. This is due to the way a ratio function is defined. For example, a ratio function for food is $\frac{FOOD}{\overline{FOOD}}$, where *FOOD* is the objective function for food production in the watershed, and $\overline{FOOD}$ is the aggregate food production for the planning horizon when continued at the current level of food production. Thus, the objective is changing production in the desired direction from its current level. A relative importance weight, say 0.25, is interpreted as: "Increasing food production from the current level is 25 percent as important as changing all other productions from their current levels." Since the denominator or the reference value is the current level, the decision maker can get an intuitive understanding of the ratio and its relative importance in percentage terms.

The weights are adequate for two reasons. One reason can be explained by the characteristics of the range of possible relative importance weights and their implication. Some of the characteristics of the range of weights are as follows:

1. The discrete weights that could be assigned to the objectives for preference relation ranges from 1 to 5. The highest ranked objective can be assigned up to the largest weight of 5. The lowest ranked objective can be assigned down to the smallest weight of 1. Therefore, the relative importance weight of the highest ranked objectives can be up to five times larger than that of the lowest ranked objectives.

2. The smallest minimum importance weight can be about 5 percent for the lowest ranked objectives. This is true for a weight set $W_a = W_b = W_c = W_d = 5$ and $W_e = 1$, which after normalization translates into the relative importance weights set $\lambda_a = \lambda_b = \lambda_c = \lambda_d = 0.24$ (24 percent) and $\lambda_e = 0.05$ (5 percent). This weight structure suggests that the lowest ranked objective is only 5 percent important, whereas other objectives are 24 percent important.

3. The largest maximum importance weight can be about 55 percent for the highest ranked objectives. This is true for a weight set $W_a = 5$, and $W_b = W_c = W_d = W_e = 1$, which after normalization translates into the relative importance weight set for $\lambda_a = 0.55$ (55 percent) and $\lambda_b = \lambda_c = \lambda_d = \lambda_e = 0.11$ (11 percent).

These characteristics describe the limits of the weighting procedures. Theoretically the procedure cannot be claimed to be adequate, because it cannot assign relative importance to the lowest ranked objective below 5 percent and the highest ranked objective above 55 percent. The range of the discrete weights need to be expanded to allow relative importance weight lower than 5 percent for the lowest ranked objective or higher than 55 percent for the highest ranked objective. For example, discrete weights ranging from 1 to 10 will provide largest relative importance difference up to 10 times between highest and lowest ranked objectives.

The smallest minimum importance weight can be as low as 2.2 percent and the largest maximum importance weight up to 70 percent.

Expansion of the range of the discrete weights will enlarge the possible combination set of relative importance weights for a preference relation. The number of solutions presented to the DM for interaction to select the best one may be large and difficult to comprehend. Hence, the weights ranging from 1 to 5 seem adequate for practical consideration.

Another pragmatic consideration is the possibility of assigning a zero weight to the lowest ranked objective if that objective would consistently rank lowest and would weight less than 5 percent relative importance. But this consideration cannot be explained theoretically. This should depend upon the judgement of the actors in the planning process.

The other reason of adequacy of the weight structure is due to the favorable scaling effect. Since the ratios are dimensionless, they are comparable. Instead of ratios, if the composite objective function is formed as a simple additive form, the problem of scaling would cause insensitivity to the proposed weight structures. This happens when the outputs of different objectives are measured in units such as tons and kilograms. In such a case, 1 percent change in output measured in tons can make a significant impact on the output measured in kilograms. But 1 percent change in output in kilograms becomes insignificant, and thus insensitive to the output in tons. This problem is avoided in the proposed composite objective function.

Ranking : Ranking is the most critical step in the process of decision maker interaction. The decision maker has to rank the objectives in order of their importance. There are altogether 5! ways of ranking the objectives for a five objective problem. For each ranking, there are numerous possible solutions for the preference relations and their weight structures. The only information the DM is provided at the ranking stage is the single objective functions' achievement levels. This information only provides knowledge of the possible achievement range. No trade off information is provided.

Each ranking reduces the feasible region to a small portion for further exploration. Each ranking, thus limits the number of candidate nondominated solutions for selection. Because of the numerous ranking possibilities, all the rankings cannot be studied and information cannot be provided for a DM's comprehensive evaluation. Hence, selecting a ranking for further exploration is crucial.

Preference relations : There are 16 preference relations within each ranking. The procedure asks the DM to select one relation for further exploration. Here again, the DM's confidence in selecting his choice relation is crucial. Each relation leads to a different set of relative importance weights ranging from 1 to several. The DM could be allowed to choose several relations. Then combining with range analysis on relative importance weights, only a small number of candidate solutions need to be generated for detail evaluation on their trade offs and output levels.

Range analysis : There is no or very little difference in solutions for some sets of relative importance weights. They indicate that those weights are insensitive to the solution. This happens when the change in the orientation of the hyperplane defined by these weights is not sufficient enough to cause a basis change. That is, the change is insufficient to leave the present extreme point solution and select another in the convex polyhedron of the feasible region. The convex polyhedron is formed by intersecting half spaces defined by the constraints. The basis will not change till the orientation of the hyperplane of the composite objective function becomes parallel to any of the adjacent half spaces or the edge of the polyhedron.

Range analysis is useful in such cases. Redundant sets of weights can be avoided before running through the model. Most of the LP packages are equipped with range analysis.

Implementation Practicality

Discussions on practicality for field implementation are focused on the availability of the necessary equipment such as computer facilities and software in a developing country context. In a country like Nepal, a large computation facility is not currently present. The LP software that could be run on personal computers would be most practical. LINDO (Scharge, 1985) was found quite adequate for this model. The test problems were successfully run with this software with the version named HYPERLINDO.

HYPERLINDO can accept problems up to 16,000 non-zero element matrix, 2000 decision variables and 200 rows. This runs under the PC DOS operating system and requires a minimum of 512K memory with a math co-processor chip. A math co-processor chip, 640K memory, and a hard disk with minimum of 1 meg are recommended. This equipment is portable. Therefore, the model can be applied in any field situation.

Chapter VI

SUMMARY AND DISCUSSIONS

A land use planning model is developed for the Nepalese Hill areas as a multi-objective programming problem. The model contains five objectives incorporated within a composite objective function. The objectives are increasing food, fodder, and fuelwood production and decreasing soil loss and costs. These objectives reflect the problems and priorities dominating the prevalent subsistence farming economy. The model views the land use planning as a socio-political process of decision making for the allocation of land to various competing uses in time and space. This process of decision making is enhanced by the weighting technique developed in the model.

The weighting technique generates a set of efficient alternative plans within desired preference relations among objectives instead of a single optimal plan. The solutions that the model generates for various weight structures and policy defined constraints provide information for decision making. The time flow of achievement levels of the objectives and their trade-offs in each solution provide the guidelines for evaluating the alternative plans. However, a solution becomes infeasible when periodic growth rates of the achievement levels are set tight. The achievement levels can be adjusted to get a feasible solution, but this would require that deficit achievement to be met from outside.

The model is successful in structuring the identified problem in mathematical forms and deriving meaningful solutions to the defined objectives. The model adopted the Model I version of the timber harvest scheduling (Johnson and Scheurman, 1977) to define the decision variables, resource constraints and periodic achievement level constraints. Decision variables can accept the technical coefficients responsive to all five objectives and be traced through planning periods.

The model is developed as an LP problem for its simplicity and availability of advanced computer packages to solve such a problem. The test runs for the demonstration problem were successfully accomplished with a commercially available mathematical programming package called HYPERLINDO (Scharge, 1985) on a personal computer. The model can be applied in any field situation in developing countries because of the portability of the personal computers.

Further research should be performed to modify the model as a mixed integer programming problem to accommodate location specific areas as the integer variables. The model can be further modified to accommodate a price driven market economy, where it imposes significant influence in land use planning decisions. This would require an acceptable technique of projecting future trends of direct prices or shadow prices of the land use outputs.

The quality of the model generated plans depends upon the quality of input data, such as yield estimates of various crops, land classification system, land use options and their management regimes. Further research in these areas will enhance the performance of the model.

In conclusion, a foundation has been laid for constructing a comprehensive model for land use planning in a subsistence farming economy in developing countries. The model generates useful efficient alternative plans serving multiple objectives connected in time and space, and evaluates them through interaction with the decision maker. The model offers the opportunity to analyze land use planning as an integrated planning process coordinating diverse multi-sector objectives. The model should be useful for designing rural development programs with emphasis on renewable natural resource development activities.

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Appendix I

FOOD PRODUCTION COEFFICIENTS

Annual food grain yields for various crops are estimated in the Table 16. for land class I and II based upon various information sources. These values for land classes III to VIII are extrapolated from the value for class II by the following relation

$$Y_{i+1} = 0.9\ Y_i$$

where, Y_i is the annual yield for class i, i = II , III , ... , VIII.

Table 16. Annual Food Grain Yields.

Land capability class Land use combination	Multiple cropping intensity (MCI)[a]	Grain yields (kg/ha)[b]	MIC*Grain yield (kg/ha) y	Food energy (cal./ 100 gm)[c] C	Rice equivalent yield (kg/ha) d
Land capability class I.					
Irri. Terr.	1.15				2226.8
Rice	0.90	2300.0	2070.0	341	
Wheat	.25	6500.0	162.5	329	
Dry Terr.	2.61				2023.0
Maize	1.00	900.0	900.0	349	
wheat	1.00	650.0	650.0	329	
Millet	0.61	800.0	488.0	332	
Land capability class II.					
Irr. Terr.	1.15				2062.8
Rice	0.90	2150.0	1935.0	341	
Wheat	0.25	530.0	132.5	329	
Dry Terr.	2.61				1907.6
Maize	1.00	900.0	900.0	349	
Wheat	1.00	530.0	530.0	329	
Millet	0.61	800.0	488.0	332	

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Table 16 continued.

[a] Multiple cropping index (MCI) is the sum of areas planted to different crops and harvested during the year, divided by the total cultivated area. MCI for irrigated terrace (khet) and dry land terrace (bari) are adopted from Plan for Integrated Development of Phewa watershed, IWM/PTR/12, Dept. of Soil conservation and Watershed Management, Kathmandu, Nepal, 1980. Detail breakdown by individual crops is the informal estimation from personnel observation.

[b] Estimated yields of various crops adopted from Resource Conservation and Utilization Project, project No. 367-0132, Appendix (Ja), vol. II, USAID , Kathmandu, Nepal.

[c] Source: Food composition Table for use in East Asia. FAO. Food Policy and Nutrition Division, 1972.

[d] Rice equivalent yield computed from the relation

$$\frac{c_1y_1 + c_2y_2}{c_1}$$

for irrigated terrace and

$$\frac{c_3y_3 + c_4y_4 + c_5y_5}{c_1}$$

for dry land terrace,

where, c = food energy and y = MCI*grain yield; subscripts are: 1 - irrigated rice, 2 - irrigated wheat, 3 - dry land maize, 4 - dry land wheat and 5 - dry land millet.

Appendix II

FODDER PRODUCTION COEFFICIENTS

Average annual fodder yields for various land uses are estimated in the Table 17 for the watershed. The values for irrigated terrace and dry land terrace are assumed to be that of land class I and the values for subsequent land classes are computed from the following relation

$$Y_{i+1} = 0.9\ Y_i$$

where, Y_i = the yield in class i, i = I , II ,... , VIII.

The values for unmanaged pasture, managed pasture, unmanaged forest, managed forest and scrub are that of the average land class, here assumed to be class V. The values for land classes I to IV are computed by the following relation

$$Y_i = 1.1\ Y_{i+1}$$

where, Y_i = yield of class i, i = I , II ,..., V.

The values for land classes VI to VIII are computed by the following relation

$$Y_{i+1} = 0.9\ Y_i$$

where, Y_i = yield of class i, i = V ,..., VIII.

Table 17. Annual Fodder Yields.

Land use	MCI[a]. Kg/ha	Yield[b] Kg/ha	TDN[c] Kg/ha	Total TDN
Irrigated Terrace	1.15			1184.15
Rice straw	0.90		1130	
Wheat straw	0.25		205	
Dryland Terrace	2.61			773.49
Maize stalk	1.0		258	
Wheat straw	1.0		258	
Millet straw	0.61		509	
Unmanaged pasture	1	1200	148.2	148.2
Managed pasture	1	6000	741.0	741.0
Unmanaged forest	1	3000	434.8	434.8
Managed forest	1	5000	724.7	724.7
Scrub	2			279.2
Leaf fodder	1	1500	217.4	
Grass	1	500	61.8	

[a] As explained in Appendix I for cultivated land.

[b] As cited in Flemming (1983).

[c] Adopted from Resource Conservation and Utilization Project, Project No. 367-0142, Appendix (Ic), Vol. II(c), USAID, Kathmandu, Nepal, 1980.

Appendix III

FUELWOOD PRODUCTION COEFFICIENTS

Average annual fuelwood yield for various land uses are estimated in Table 18 for the watershed. These values are estimated to be that of the average land class, which is assumed to be class V. The values for land classes I to IV are computed by the following relation

$$Y_i = 1.1\ Y_{i+1}$$

where, Y_i = yield in class i, i = I ,..., IV.

The values for land classes VI to VIII are computed by the following relation

$$Y_{i+1} = 0.9\ Y_i$$

where, Y_i = yield of class i, i = V ,..., VIII.

Table 18. Annual fuelwood yields.

Land use	Sustained Yield[a] (m^3/ha/yr)
Unmanaged forest	12.0
Managed forest	20.0
Scrub	4.0

[a] As cited in Flemming (1983).

Appendix IV

CROPPING MANAGEMENT FACTOR

Table 19. Cropping management factor values for various land uses in Phewa-tal watershed.

Land use	Annual C value	Source
Irrigated terrace	0.6	Impat, 1981
Dryland terrace	0.55	Fetzer and Jung, 1979
Unmanaged pasture	0.013	SCS, 1972
Managed pasture	0.003	do
Unmanaged forest	0.025	Dissmeyer and Foster, 1980
Managed forest		do
(Converted from irrigated terrace, dry land terrace, and unmanaged pasture)		
(a) First period	0.013	
(b) Second period	0.008	
(c) Third period	0.003	
(Converted from scrub land)		
(a) First period	0.005	
(b) Second period	0.004	
(c) Third period	0.003	
(Converted from unmanaged forest)		
(a) First period	0.025	
(b) Second period	0.014	
(c) Third period	0.003	

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Table 19 continued.

Land use	Annual C value	Source
Protected forest		do
(Converted from irrigated terrace), dry land terrace, and unmanaged pasture)		
(a) First period	0.013	
(b) Second period	0.008	
(c) Third period	0.003	
(d) Fourth period	0.002	
(e) Fifth period	0.001	
(Converted from scrub land)		
(a) First period	0.005	
(b) Second period	0.004	
(c) Third period	0.003	
(d) Fourth period	0.002	
(e) Fifth period	0.001	
(Converted from unmanaged forest)		
(a) First period	0.025	
(b) Second period	0.014	
(c) Third period	0.003	
(d) Fourth period	0.002	
(e) Fifth period	0.001	
Scrub land	0.005	do

Appendix V

COST COEFFICIENTS

Annual cost of production is calculated by following relation

(1) $\frac{C_1T_1 + C_2T_2}{C_1 + C_2}$ for irrigated terrace cultivation

(2) $\frac{C_3T_3 + C_4T_4 + C_5T_5}{C_3 + C_4 + C_5}$ for dry land terrace cultivation

where, C = multiple cropping index (Appendix I)
T = cost of production of individual crops (Table 20)
1 = rice
2 = irrigated wheat
3 = maize
4 = dry land wheat
5 = millet

Annual cost of production for land uses other than cultivated agriculture (unmanaged pasture, managed pasture, unmanaged forest, managed forest, scrub, and protected forest) is assumed zero. All the costs (some annual costs as well) are incorporated in the establishment or afforestation cost.

Periodic cost of production for continuation of the cultivated land use is computed by multiplying the annual cost of production by five.

Total cost in the period of land use conversion is the sum of the cost of land use conversion and annual cost of production of the new land use multiplied by five.

Table 21 presents the annual cost of production and cost of land use conversion for the various land uses.

Table 20. Estimated cost of production of various crops (1986)

S. No.	Crop	Annual cost (Rs/ha)
1	Rice	4800.00
2	Irrigated wheat	4200.00
3	Maize	6100.00
4	Dry land wheat	4200.00
5	Millet	1863.00

Source: Personal computation.

Table 21. Annual cost of production and cost of land use conversion (Rs/ha) (1986).

Land use	Annual cost of production	Cost of land use conversion from			
		Dry land terrace	Unmanaged pasture	Unmanaged forest	Scrub
Irrigated terrace					
I	4670.00	2654.00	3820.00	5820.00	4220.00
II	"	5621.00	12220.00	14110.00	12510.00
III	"	"	24770.00	26770.00	25170.00
IV	"	"	"	"	" "
V	"	5140.00	32000.00	34000.00	32400.00
VI	"	"	38400.00	40400.00	38800.00
VII	"	5315.00	39128.00	41128.00	39528.00
VIII	"	6320.00	46000.00	48000.00	46400.00
Dry land terrace					
I	4375.00		1665.00	3665.00	2065.00
II	"		5640.00	9640.00	6040.00
III	"		19180.00	21180.00	19580.00
IV	"		19180.00	21180.00	19580.00
V	"		26860.00	28860.00	27260.00
VI	"		33760.00	35760.00	34160.00
VII	"		34460.00	36460.00	34860.00
VIII	"		41120.00	43120.00	41520.00
Managed pasture					
I - VIII		8600.00	8600.00	10600.00	9000.00
Managed and Protected forest					
I - VIII		10738.00	10738.00	8000.00	11138.00

Source: Personal computation.

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