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Land Allocation Decisions: A Mathematical Programming Framework Focusing on Quality of Life†

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This paper reports the structure and analysis of an approach to land allocation decisions based on inputs from an interdisciplinary group operating in a workshop approach. A typical land use problem is formulated, three land uses (three system variables) were considered, and their impact on quality of life was evaluated by means of ecological, economic, political, and sociocultural variables (20 objective variables). The impact on quality of life of the objective variables was accommodated through a value standardization approach. The result was a nonlinear programming optimization problem, which was solved for our numerical example. The value of this approach, and its limitations, are discussed.

1. Introduction

This paper offers an initial view, from both a human and an ecological viewpoint, of some of the problems associated with land use planning. We offer a quantitative framework within which land use decisions can be made. The approach involves looking at the decision as maximizing a consensus of

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9. Man-initiated energy consumption, $X_{9,t}$	8	−	High constant	Increasing and then decreasing	Increasing
Sociocultural					
10. Population size, $X_{10,t}$	14	+ then −	Increasing	Increasing and then decreasing	Decreasing
11. Social differentiation, $X_{11,t}$	16	+ then −	Increasing	Increasing and then decreasing	Increasing
12. Cultural heterogeneity, $X_{12,t}$	14	+ then −	Increasing, decreasing, and then increasing	Decreasing and then increasing	Increasing and then decreasing
13. Sociopsychological (solidarity), $X_{13,t}$	6	+	Decreasing	Decreasing and then increasing	Decreasing
14. Information advantage, $X_{14,t}$	20	+	Decreasing	Decreasing and then increasing	Decreasing and then increasing
Political					
15. Scope of government services, $X_{15,t}$	13	+		Increasing	
16. Uses of government services, $X_{16,t}$	6	+		Increasing	
17. Political participation, $X_{17,t}$	18	+		Increasing	
18. Poverty tax base, $X_{18,t}$	8	+		Increasing	
19. Political power advantage, $X_{19,t}$	9	+		Increasing	
20. Dollar investment, $X_{20,t}$	10	+ for low, − for high		Constant	

TABLE 3. Equations standardizing quality-of-life indicators to value units and showing impact of land allocation

Variable	Standardization equation	Equations relating variable to land use or another variable
1. $X_{1,1}$	$-2+0{\cdot}008X_{1,t}$	$1800+2000A_1-1200A_1^2$
2. $X_{1,2}$	$-2+0{\cdot}008X_{1,t}$	$1300+2000A_2-1000A_2^2$
3. $X_{1,3}$	$-2+0{\cdot}008X_{1,t}$	$1000+2000A_3-1000A_3^2$
4. $X_{2,1}$	$-10+\frac{16}{1+[0{\cdot}331(X_{2,t}-98)]^2}$	$90+13A_1-13A_1^2$
5. $X_{2,2}$	$-10+\frac{16}{1+[0{\cdot}331(X_{2,t}-98)]^2}$	92
6. $X_{2,3}$	$-10+\frac{16}{1+[0{\cdot}331(X_{2,t}-98)]^2}$	90
7. $X_{3,1}$	$-10+7e^{0{\cdot}01X_{3,t}}$	$-60+650A_1-410A_1^2$
8. $X_{3,2}$	$-10+7e^{0{\cdot}01X_{3,t}}$	$95-100e^{-0{\cdot}29A_2}$
9. $X_{3,3}$	$-10+7e^{0{\cdot}01X_{3,t}}$	$-10+22A_3-12A_3^2$
10. $X_{4,1}$	$-10+\frac{18}{1+[5{\cdot}6(X_{4,t}-0{\cdot}16)]^2}$	$0{\cdot}5+0{\cdot}13A_1-0{\cdot}13A_1^2$
11. $X_{4,2}$	$-10+\frac{18}{1+[5{\cdot}6(X_{4,t}-0{\cdot}16)]^2}$	$0{\cdot}25+0{\cdot}33A_2-0{\cdot}55A_2^2$
12. $X_{4,3}$	$-10+\frac{18}{1+[5{\cdot}6(X_{4,t}-0{\cdot}16)]^2}$	$0{\cdot}16+4A_3-0{\cdot}52A_3^2$
13. $X_{5,1}$	$-5+\frac{12}{1+11e^{-0{\cdot}85X_{5,t}}}$	$1{\cdot}1+7{\cdot}2A_1$

14.	$X_{5,2}$	$\dfrac{-5+12}{1+11e^{-0.85X_{5,t}}}$	$0.2+0.1A_2-0.32A_2^2$
15.	$X_{5,3}$	$\dfrac{-5+12}{1+11e^{-0.85X_{5,t}}}$	$1.6-1.4A_3+2.1A_3^2$
16.	$X_{6,1}$	$10-20X_{6,t}$	$0.05e^{0.00003(X_{10,1}-5000)}$
17.	$X_{6,2}$	$10-20X_{6,t}$	$2.5A_2$
18.	$X_{6,3}$	$10-20X_{6,t}$	$1.5+2.5A_3-3.13A_3^2$
19.	$X_{7,1}$	$-2+25X_{7,t}$	$e^{0.000046(X_{10,1}-5000)}$
20.	$X_{7,2}$	$-2+25X_{7,t}$	$42+140A_2$
21.	$X_{7,3}$	$-2+25X_{7,t}$	$62+166A_3-118A_3^2$
22.	$X_{8,1}$	$6(1-e^{-6.36X_{8,t}})-3.5X_{8,1}$	$0.00004X_{10,1}+0.5$
23.	$X_{9,1}$	$9e^{-2.2X_{9,t}}$	1000
24.	$X_{9,2}$	$9e^{-2.2X_{9,t}}$	$0.3+2A_2-3.3A_2^2$
25.	$X_{9,3}$	$9e^{-2.2X_{9,t}}$	$0.3A_3$
26.	$X_{10,1}$	$0.0016X_{10,t}-1.6\times10^{-1}X^2_{10,t}$	$257\,000A_1-28\,000$
27.	$X_{10,2}$	$0.0016X_{10,t}-1.6\times10^{-1}X^2_{10,t}$	$94.5+111A_2-556A_2^2$
28.	$X_{10,3}$	$0.0016X_{10,t}-1.6\times10^{-1}X^2_{10,t}$	$32-12A_3$
29.	$X_{11,1}$	$0.0006X_{11,t}$	$500e^{0.00004(X_{10,1}-5000)}$
30.	$X_{12,1}$	$0.8X_{12,t}-0.04X^2_{12,t}$	$28+0.053\left[\left(\dfrac{X_{11,1}}{10\,000}\right)^3-38\left(\dfrac{X_{11,1}}{10\,000}\right)^2+252\left(\dfrac{X_{11,1}}{10\,000}\right)-360\right]$
31.	$X_{12,2}$	$0.8X_{12,t}-0.04X^2_{12,t}$	$22-48A_2+48A_2^2$
32.	$X_{12,3}$	$0.8X_{12,t}-0.04X^2_{12,t}$	$8+20A_3-20A_3^2$
33.	$X_{13,1}$	$-3+0.6X_{13,t}$	$\dfrac{9}{1+8e^{-0.0006(5000-X_{11,1})}}$
34.	$X_{14,1}$	$\dfrac{20}{\pi}\tan^{-1}[8\pi(X_{14,t})]$	$0.22(1-e^{-0.0005X_{10,1}})$

TABLE 3. (*contd.*)

	Variable	Standardization equation	Equations relating variable to land use or another variable
35.	$X_{14,2}$	$\frac{20}{\pi}\tan^{-1}[8\pi(X_{14,t})]$	$0{\cdot}167-1{\cdot}1A_2+37A_2^2$
36.	$X_{14,3}$	$\frac{20}{\pi}\tan^{-1}[8\pi(X_{14,t})]$	$0{\cdot}05-0{\cdot}58A_3+0{\cdot}73A_3^2$
37.	$X_{15,1}$	$-10+14(1-e^{-0{\cdot}26X_{15,t}})$	$3+8(1-e^{-0{\cdot}0002X_{11,1}})$
38.	$X_{16,1}$	$-3+10(1-e^{-0{\cdot}01X_{16,t}})$	$40+\frac{25}{\pi}\tan^{-1}[0{\cdot}001\pi(X_{11,1}-200)]$
39.	$X_{17,1}$	$-10+18(1-e^{-0{\cdot}008(X_{17,t}-18)})$	$20+50(1-e^{-0{\cdot}003X_{11,1}})$
40.	$X_{18,1}$	$-1+\frac{8}{\pi}\tan^{-1}[0{\cdot}0007(X_{18,t}-2000)]$	$1000+1500(1-e^{-0{\cdot}003X_{11,1}})$
41.	$X_{19,1}$	$3+\frac{10}{\pi}\tan^{-1}[0{\cdot}03(X_{19,t}-40)]$	$0{\cdot}0015X_{11,1}+10$
42.	$X_{20,1}$	$0{\cdot}01X_{20,t}$	$-100A_1$
43.	$X_{20,2}$	$0{\cdot}01X_{20,t}$	$-40A_2$

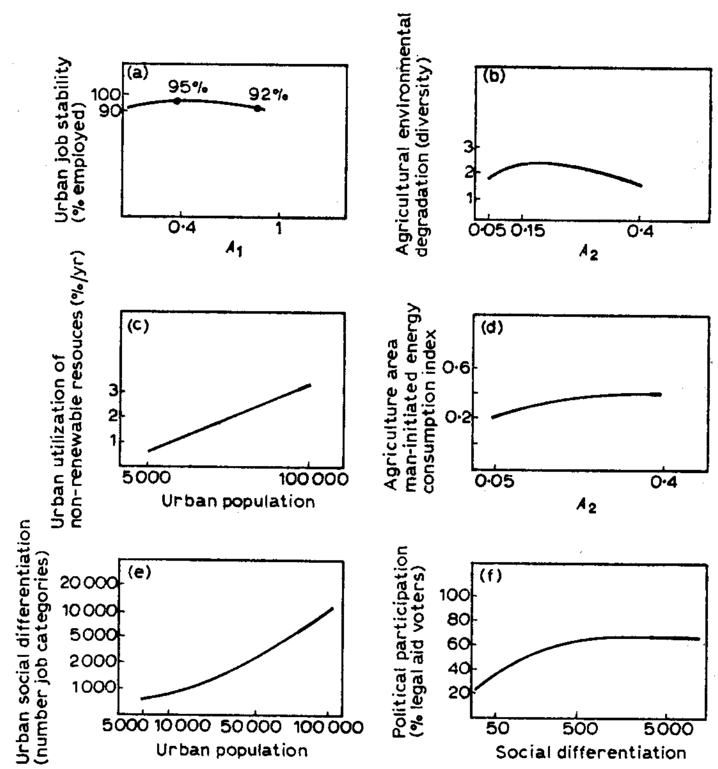

Figure 2. Effect of land use upon quality-of-life indicators. (a) Urban job stability *vs.* urban area; (b) agricultural area environmental quality *vs.* irrigated acreage; (*c*) percent annual utilization of non-renewable resources *vs.* urban population; (d) agriculture area man-initiated energy index *vs.* irrigated area; (e) urban social differentiation *vs.* urban population; (f) regional political participation *vs.* social differentiation.

density in the urban area as a measure of the non-renewable resource demand (Figure 2(c)).

As population density grows from a population of about 5000 to a population of 100 000 the annual consumption of non-renewable resources is assumed to increase from about 0·5 to 3%. This trend cannot continue because in the long run the non-renewable resource would soon be depleted. This curve is somewhat unrealistic, because the non-renewable resources may well not come from the area in which the urban density that we are talking about exists, but would come from other areas and have to be paid for.

4·4. MAN-INITIATED ENERGY CONSUMPTION

We defined man-initiated energy consumption as the ratio of the energy utilized by man through fossil fuels to the energy utilized from the sun.

In the urban areas where almost the entire energy consumption depends on fossil fuels for machinery, heat, electricity, etc., the ratio is assumed to be arbitrarily 1000. The only sun utilization that we can imagine in the urban area is for growing lawn grass and gardens and solar energy for heating. Figure 2(d) predicts the effect of agricultural area A_2 upon man-initiated energy consumption in the agricultural area $X_{9,2}$.

In the agricultural areas the fossil fuel inputs are mainly through fertilizers and machinery. The use of fertilizer greatly increases the efficiency of the utilization of the sun's energy. However, a great deal of energy is also spent using fossil fuels for machinery to keep pests away and to mechanize the planting and harvesting processes. Therefore, with increased agricultural intensity resulting from increased area in agriculture, the ratio of man-initiated energy to sun-utilized energy increases due to the increased use of mechanical devices rather than human labour. Notice that the ratio is still less than 1, which indeed shows us that our agricultural areas are enabling us to support the large imbalance of fossil fuel to solar energy inputs in the city. In the range area the energy consumption from fossil fuels is low. However, we hypothesize that with increased size of the range, more intensive conservation practices are done at the expense of larger fossil fuel input (for example, jeeps, fence post holes, seeding for hay, etc.), raising the ratio of human to sunlight energy input utilized.

4·5. SOCIAL DIFFERENTIATION

Social differentiation refers to how many different types of job possibilities exist in the area as a measure of the potential job interchangeability of the area and the production diversity of the area. The degree of social differentiation is operationally defined as the number of separate job categories listed for the area. This ranges from 10 to 20 separable jobs in the "jack-of-all-trades" tribal society to the mass industrial society with approximately 40 000+ jobs.

Urban area population $X_{10,1}$ was considered a better predictor of social differentiation $X_{11,1}$ than area in urban land. Since social differentiation in the urban area affects the surrounding countryside so heavily, the social differentiation was taken to represent that for the entire area. Figure 2(e) shows the relationship between $X_{11,1}$ and $X_{10,1}$.

As population rises, social differentiation is assumed to increase exponentially within the population range dealt with in this model.

4·6. POLITICAL PARTICIPATION

Political participation $X_{17,1}$ is measured by the percentage of the voting age

TABLE 4. Comparison of effect of land allocation quality-of-life indicators

Variable	$A_1 = 0{\cdot}1, A_2 = 0{\cdot}05$	Value	$A_1 = 0{\cdot}25, A_2 = 0{\cdot}4$	Value	$A_1 = 0{\cdot}3, A_2 = 0{\cdot}4$	Value
Urban population	32 000	+3·84	80 000	0	96 000	−4
Ecological degradation (urban)	0·18	+6·4	0·29	+4·2	0·32	+3·6
Percent of non-renewable resources (annual)	1·8	−0·3	3·7	−6·9	4·3	−9
Social differentiation	500	0	2000	+2	2500	+3
Per capita income	2028	+2	2325	+2·3	2412	+2·4
Political participation	62	−5	70	−4	70	−4

population which votes in local elections. We have assumed that this may be predicted from the social differentiation in the region, as shown in Figure 2(f).

Political participation in areas of small social differentiation generally is low. We have assumed that it is in the range of 30% to 40%. As social differentiation increases, the political participation in terms of the percentage of the population voting starts to increase quite rapidly until it levels off at about 60% participation, which at present is about the highest participation to be expected in any United States regional election.

5. Value standardization curves

In standardizing the quality-of-life indicators to some equivalent scale, a decision has to be made as to what units to use. We finally selected arbitrary value units instead of converting all the quality-of-life indicators to dollars, which is the usual approach in most quantitative decision making techniques. There were several reasons for this decision.

(a) *Dollars are not linear.* For example there are thresholds in dollar "value". \$100 000 is worth more than twice as much as \$50 000 if you need something costing \$75 000.

(b) *Dollars are not standard* between individuals even though we think they are. Therefore, when two people standardize their valuables to a dollar scale, they would then have to standardize their dollars to each other.

(c) *Dollars have connotative value* of business and money markets. Thus, it is difficult to separate local decisions evaluated in dollars from larger-scale monetary considerations.

(d) The *connotations of money are offensive* in standardizing some " human " values as, e.g., social solidarity or habitat diversity.

Thus, an initial-seeming advantage of dollar standardization, the ease of thinking and evaluating in dollars, breaks down to a liability. We therefore chose value units over an arbitrary scale of +10 to −10. While value standardization to such units is a difficult task, it at least does not suffer from many of the difficulties as does the dollar as a standard unit.

Although the value standardizations we have chosen are arbitrary and would likely have to be re-evaluated and modified for application to a specific problem, they do represent a step toward trying to standardize ecological, political, economic, and sociological variables to " quality of life "; and these variables should be considered in planning decisions. However, the way that we standardized the variables one to another can be said to apply only to this specific problem. Although the same quality-of-life indicators might apply to other regions, the value of them would certainly change from region to region.

We would expect that in a specific region the value standardization curves could represent the consensus values of elected officials or the planning board representing their constituencies. In our case example the value curves represent the average values of our workshop participants. In the case of our value curves there was considerable variance, representing value disagreement among workshop participants. The same would be expected in the case of the regional decision-making body in a real situation.

The assumption was made, perhaps simplistically, that each of the quality-of-life indicators had the same value over each of the land use areas. This simply means that the curves relating the quality-of-life indicators to value units were the same for each of the three areas. Understandably, certain desires of a community vary when we go from an urban to a range area. However, in many cases these differences in values were handled by altering the definition of the quality-of-life indicator from one land use to the other. For example, in the urban area the environmental degradation index was related to air pollution, whereas in the range area it was related to erosion. Certainly, however, this assumption is open to criticism. Probably a more complete formulation of the problem would have different value standardization curves for each land use type.

The value standardization curves for the same six quality-of-life indicators (as discussed in the section on the effects of land use on quality-of-life indicators) are reviewed below.

5·1. EMPLOYMENT STABILITY $X_{2,i}$

Figure 3(a) shows employment stability (percent of labour force employed) standardized to value units $V_{2,1}$. The 0 value is 96% employment—assumed to be the national average. Having 98% employment gives the highest value of +6 units. Having less than 96% employment results in a negative value, with −10 being reached at 85% employment ($\leqslant$ 85%). Above 98% employment the value drops since there is no surplus labour force to meet fluctuations in demand.

5·2. ENVIRONMENTAL QUALITY INDEX $X_{6,i}$

The value standardization of environmental quality index $V_{6,i}$ is given in Figure 3(b). It is postulated that a high diversity is aesthetically desirable and therefore raises quality of life. High diversity is quite desirable (+7). Low diversity, while undesirable, is not very undesirable (−4 at the minimum).

5·3. PERCENTAGE ANNUAL USE OF NON-RENEWABLE RESOURCES $X_{8,i}$

The value standardization for $V_{8,i}$ is given in Figure 3(c). Above 0·5% annual use of non-renewable resources value declines, remaining positive until about 1·5%. It then drops steadily until −10 value is reached at 5% annual usage. Below 0·5% usage value also drops, since it is assumed that man has become, in some sense, dependent upon his non-renewable resources and must continue some harvesting to maintain his system. A high per cent utilization (above 5%) is seen as extremely negative in value. Such a high use rate rapidly closes out options for future generations.

5·4. MAN-CONTROLLED ENERGY CONSUMPTION $X_{9,i}$

Following the approach of Odum (1971), we consider the ratio of man-controlled energy inputs to solar input utilization an important ecological indicator for system stability. The larger the ratio, the more man must *depend* on his energy input to maintain stability (fossil fuels are his major source of exogenous energy input). For example, in a city stability is extremely dependent upon machines which run on fossil fuels. Loss of these fuels is a source of potential system instability.

Figure 3(d) shows the value standardization for man-controlled energy consumption $V_{9,i}$. The range is +4 to −4. For very small ratios the value is positive; for larger ratios the value is negative. The value drops off rapidly

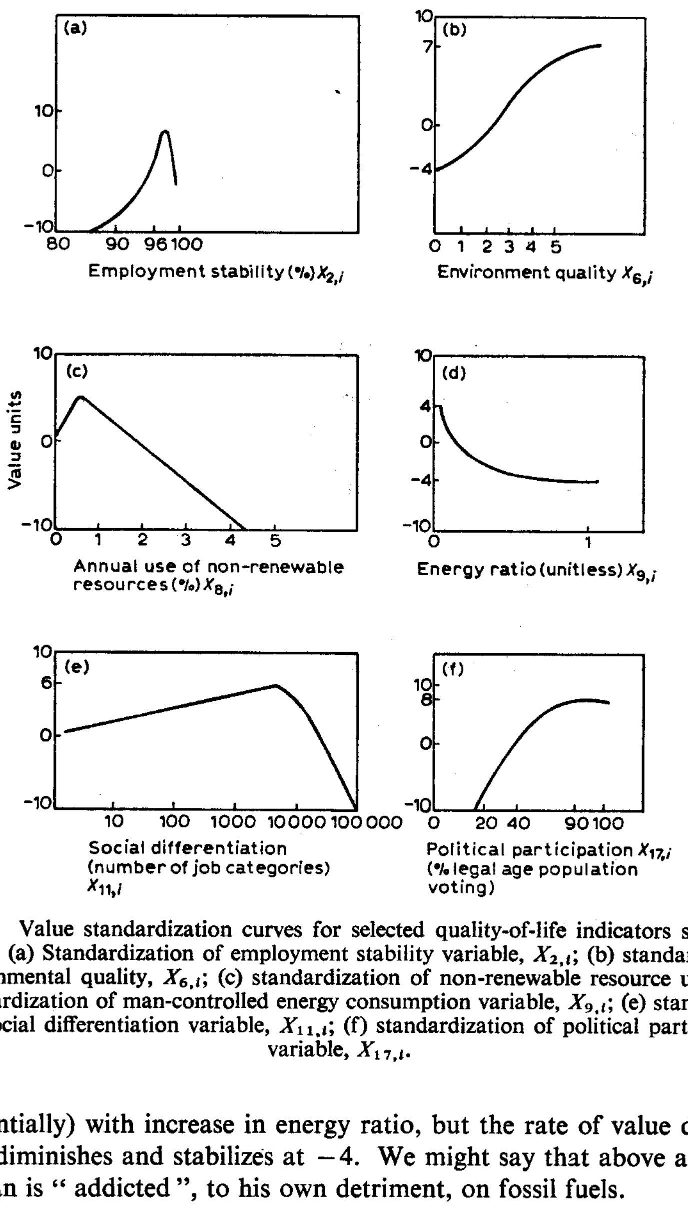

Figure 3. Value standardization curves for selected quality-of-life indicators shown in Figure 2. (a) Standardization of employment stability variable, $X_{2,i}$; (b) standardization of environmental quality, $X_{6,i}$; (c) standardization of non-renewable resource use, $X_{8,i}$; (d) standardization of man-controlled energy consumption variable, $X_{9,i}$; (e) standardization of social differentiation variable, $X_{11,i}$; (f) standardization of political participation variable, $X_{17,i}$.

(exponentially) with increase in energy ratio, but the rate of value drop-off rapidly diminishes and stabilizes at -4. We might say that above a certain ratio man is " addicted ", to his own detriment, on fossil fuels.

5·5. SOCIAL DIFFERENTIATION $X_{11,i}$

Figure 3(e) gives the value standardization curve for social differentiation.

With small social differentiation we assume there are not enough " information resources " to logistically handle social systems of the sort in the U.S. Increase in social differentiation (specialization) is seen as desirable. With too much specialization, however, value drops; people become irreplaceable with little job interchange possible. Trust in the interchange of job services *breaks down* as one loses sight of just what the other fellow is doing. This leads to unconstrained conflict (seen as negative in value). We emphasize that conflict per se is an important asset to a social system since it promotes the search for " variety ". What is bad is a system without conflict-resolution capacities by which " variety " or alternates are selected and introduced. The elimination of conflict or the presence of unconstrained conflict is a survival problem for a variety-seeking system in a changing environment.

5·6. POLITICAL PARTICIPATION $X_{17,\,i}$

Figure 3(f) shows value standardization for political participation. A very low voting percentage is seen as a measure of a closed system, where no real political choice is available to the voters, while a high degree of participation is probably indicative of an open political system. While normally high for a town the size of Riverton, due to the manager form of government, the closed elite system and the generally nontolerant nature of the populace makes political participation low here. Poor and uneducated people normally do not like the manager form of government and hence do not participate as much as in other forms for at least two reasons. First, government is in the hands of an expert, the city manager, and is not run by people like one's neighbour. Second, councilmen are elected in at-large elections and may not live in the poorer sections in town. Together, these seem to be powerful detriments to poor people's participation in politics in small, city-manager cities. The closed elite system and nontolerant attitudes do not promote much hope in having one's view heard or respected. Even one's vote may be considered meaningless.

The goal of widespread political participation is that of self-realization of one's own goals in society. In the process of political participation one would hope for continued personal self-development as well. Then as one's political efficacy increases, one's satisfaction with participation and its results will increase.

Political participation is seen as important to the decision maker. The average political participation for a local or regional election was assumed to be 40%, and this is the 0 value point. Above this point the value of participation increases quite rapidly until a +8 value is reached at 90% participation, after which there is no further increase in value. Below 40%

participation the value goes negative and drops extremely rapidly. A -10 value is reached at 20% participation.

6. Formulation of problem constraints

There are two physical constraints in the Riverton problem, both evidenced directly on the system variables. These are that all the land area must be taken up by the land use types or, alternatively, that the fraction of land use in the three land uses must sum to one.

The other physical constraint deals with the Riverton problem statement that intensive water use can extend as far as Plane. This is interpreted quantitatively that at most 40% of the total area can be in intensive water use (intensive water use land is taken to mean urban land plus agricultural tillage land).

The other constraints are on the objective variables. Basically, they are that no *very negative values* of any of the quality-of-life indicators will be allowed. This is done by constraining the value $V_{k,i}$ of each of the quality-of-life indicators to be greater than -10.

Example cases where this constraint applies are as follows. For percentage annual use of non-renewable resources, $X_{8,i}$, above 5% the value $V_{10,i}$ is less than -10. The constraint that the value cannot be less than -10 thus constrains $X_{8,i}$ to be less than 5%. Similarly, with political participation, $X_{17,i}$, the value $V_{17,i}$ goes below -10 for less than 20% of the voting age population actually voting. This is such a low voter turnout that systems having lower than this cannot be said to be participatory democracies, and voting percentage is therefore constrained to be above 20%.

7. Formulation of the problem as a non-linear programming problem

The problem as outlined in the preceding sections can be structured as a non-linear programming problem to maximise quality of life 10 years after the decision process.

7·1. OBJECTIVE FUNCTION

Maximize quality of life (sum of the value of the quality-of-life indicators):

$$\text{maximize} \sum_{k=1}^{20} \sum_{i=1}^{3} A_i V_{k,i} \cdot A \qquad (1)$$

where $V_{k,i}$ is value per acre of land use type i, and A is the total acreage (hence, $A_i \cdot A$ is equal to the actual acreage in land use i).

7.2. CONSTRAINTS

The constraints are as follows:

$$\sum_{i=1}^{3} A_i = 1 \quad \text{(all land used)}$$

$$A_1 + A_2 \leqslant 0{\cdot}4 \quad \text{(intensive water use limit)}$$

$$V_{k,i} \geqslant -10 \quad (\text{for } i = 1, \ldots, 3; \quad k = 1, \ldots, 20).$$

The $V_{k,i}$ are functions of $X_{k,i}$ (by the value standardization curves), or in the notation we use:

$$V_{k,i} = f^k(X_{k,i}).$$

Similarly, the $X_{k,i}$ are related to land use A_i or other quality-of-life indicators $X_{j,i}$:

$$X_{k,i} = g^k(A_i, X_{j,i}).$$

Therefore,

$$V_{k,i} = f^k(g^k(A_i, X_{j,i})).$$

Since all $X_{k,i}$'s can eventually be linked back to A_i, we can say

$$V_{k,i} = h^k(A_i) \tag{2}$$

where h^k is a combination of f^k and g^k. In many cases it is non-linear.

Substituting into equation (1) from equation (2) we get

$$\text{maximize} \sum_{k=1}^{20} \sum_{i=1}^{3} h^k(A_i) \cdot A_i \cdot A \tag{3}$$

which relates the objective function back to the system variables A_i.

8. Solution to the non-linear programming Riverton land use allocation problem

Since there were only three variables in the problem, and in fact only two independent variables, it was possible to graph the objective function for various values of A_1 and A_2 and then to check the quality-of-life indicators at the relative maxima to see if any constraints were unsatisfied—an *ad hoc* optimization approach. The results are shown in Figure 4 with overall quality of life labelled "Value" plotted against agricultural land A_2 for values of A_1 varying in steps of 0·05 from 0·05 to 0·4. For the range of reasonable solutions the $V_{k,i}$ were always within the range +10 to −10, so the constraint $V_{k,i} \geqslant -10$ was always satisfied.

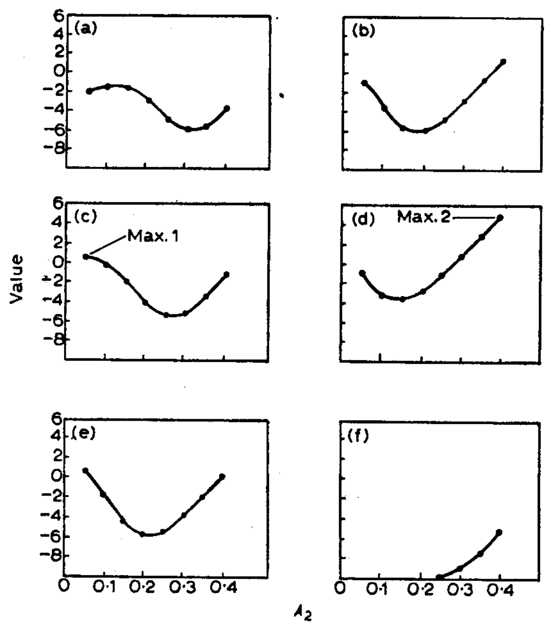

Figure 4. Quality-of-life graphed against agricultural area A_2 for varying percentages of urban area A_1. (a) $A_1 = 0{\cdot}05$; (b) $A_1 = 0{\cdot}20$; (c) $A_1 = 0{\cdot}10$; (d) $A_1 = 0{\cdot}25$; (e) $A_1 = 0{\cdot}15$; (f) $A_1 = 0{\cdot}30$.

The results are rather interesting. There are two maxima labelled. Max. 1 is the maximum value of the objective function satisfying the constraint $A_1+A_2 \leqslant 0{\cdot}4$. The cumulative quality of life value at Max. 1 is 0·49 with 10% of the area urban (urban population of 32 000), 5% in intensive agriculture, and 85% in range. This represents essentially the same conditions of the problem as exacted before the decision to develop the aquifer was considered.

The other maximum value, labelled Max. 2, is the maximum value for the problem with no water constraint. It has a value of 4·86 with $A_1 = 0{\cdot}25$, $A_2 = 0{\cdot}4$, and $A_3 = 0{\cdot}35$. This is a higher value than Max. 1. It represents large-scale development of the subterranean aquifer for agricultural purposes along with a large urban centre (80 000 population). With a restrictive water development constraint the optimal value is achieved at a state of undeveloped resources, while when the constraint is relaxed a large development gives the optimal solution. All combinations between these two states give lessened values. This is an interesting and perhaps counterintuitive result. It is noticed in Figure 4 that increasing urban area from 0·25 to 0·3 greatly reduces the quality of life. This is probably because the ecological variables deteriorate greatly in the urban area when it increases in this range, while the major economic, sociological, and political benefits of urbanization begin to depreciate or increase more slowly. A short tabular comparison of some selected quality-of-life indicators in Table 3 brings this to light.

The idea of " optimal " solution being limited by a constraining resource has shown itself to be a major factor in many areas of resource development in the western United States. Water is certainly a most prominent limiting resource. For example, in the proposed development of oil shale reserves in western Colorado to help lessen the country's experienced oil shortage, water availability has proven the impediment to full-scale development (Metz, 1974). Man must certainly learn to reckon with resource limitations in his decision making.

All the ecologically-oriented indicators decrease with increasing land usage in urban land, while the economic, sociological, and political variables generally increase with increased land utilization in urban and agriculture usage. The reductions in quality of life evidenced by an increase from 0·25 to 0·3 in urban area (see Figure 4) are mainly due to the ecological variables' great reduction in value which is not balanced by large increases in the other variables.

Apparently, the optimal solution is extremely dependent upon the resource constraints. It seems to indicate that large-scale development should proceed if resources are available for sufficiently large-scale development. If resources for large-scale development are not available, the solution seems to indicate *no* development. A little development does not seem to be a good thing.

In general, a problem like this would be solved using a non-linear programming algorithm. In this case it was not necessary and would even have had difficulty giving a unique solution. This is due to the fact that the objective function is double peaked (see Figure 4) while the objective must be a single-peaked, smooth curve to assure a solution.

9. Discussion of difficulties and future development possibilities

There are a great many areas where our solution can be considered so simplified as to be unrealistic.

(a) Our problem analysis is *static* rather than dynamic. One would expect that a realistic planning decision would try to maximize quality of life *over* a planning horizon, rather than *at the end* of the planning horizon. Also, the effects of the decisions are dynamic and should be properly simulated.

(b) When predicting the effect of land use upon the quality-of-life indicators, it should be recognized that such predictions are *stochastic* and not *deterministic* as assumed in this model.

(c) The problem does not have any direct spatial considerations. Only the amount, not the location of the land use categories, is considered. Yet, the locations must be very important in determining the effect of allocation upon quality of life. Road and factory locations have important effects on the lives of local inhabitants.

(d) In our problem all quality-of-life indicators were assumed to depend upon either land area A_i or another indicator. In actuality, they are related to each other in a complex multidimensional fashion.

(e) The large variance in the value standardization curves due to differences of opinion about desirability of a given environmental situation makes the particular curves developed in this paper appear arbitrary. No study was made of how this variance affects the solution to the problem.

All these above deficiencies of our problem analysis were due to our decision not to overly complicate the problem so that a solution might be obtainable by presenting feasible techniques. Dynamic and stochastic optimizations are extremely difficult to solve unless very special conditions are obtained, e.g. linearity and independence of variables, and this was not the case in this problem. Adding spatial aspects would have increased the dimensionality of the problem, which would also add complexity, as would dealing with complex interactions between the quality of-life indicators.

Another question about our handling of the Riverton problem is whether this technique results in a politically expedient or even realistic solution. We chose a sparsely populated area partially for that purpose. It was felt that since the solution does represent a consensus of the interested groups in the area the decision might be accepted by the populace. Perhaps decision by consensus is idealistic in the political milieu today. Certainly it is unrealistic for densely populated systems where people do not feel close to the decisions made for their region. Of course, it might be argued that local decisions on land allocation exist within a larger regional framework, and the political realities of such frameworks must not be neglected. A more realistic treatment would certainly have to consider the external political milieu.

Despite all the drawbacks, we feel this paper represents a start towards the consideration of the complexity of human values, desires, and intentions in decision making in resource and land management. It seems that analogous reasoning must be used for decisions in all types of resource management problems. Most resource management problems like this one involve a mix of uncontrolled and controlled resources. They have a high degree of interaction between the resource system and the human (sociological) system.

They must handle conflicts that arise between various interest groups. They must reach decisions about allocation of resources that often produce contrasting effects with respect to system objectives.

We feel that this approach to decision-making has widespread application, both to resource management problems and to various decision-making organizations. We have put speculation about the impact of decisions on growth and change in an area into a quantitative framework. Further efforts must be made in the future to increase the degree of credibility of resource planning. Certainly the value problem is a difficult one and one which will require careful study before values can be quantified in a regional area. To some extent, success in the use of techniques like this depend on careful study of the resource area to be planned.

If spatial considerations are introduced, this technique could be combined with maps to show what the area would look like under various planning decisions and strategies, thereby giving a pictorial extension to the model. This is valuable for the possibility of examining the effects of decisions and including subjective considerations on what people want their area to look like. People perhaps can express some of their values through visual cues that they might find difficult to express more abstractly.

We feel that this work offers the following ideas.

(a) It gives a quantitative technique with potential widespread application in aiding resource allocation decisions, which places the resource planner's decision inside the human framework wherein it is made.

(b) It points out the need for study of objectives, system constraints, and the evaluation of values in their relationship to system behaviour resulting from planning decisions.

(c) It shows the possibility of, and need for, interdisciplinary activity in structuring system decision models when experts exist on only subunits of the system and not on the whole system itself.

(d) It points out the enormity of the tasks ahead of us in moving toward more realistic models for resource management decisions.

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community objectives under physical, financial, feasibility, and acceptability constraints. The overall objective chosen was to maximize the *quality of life* of the community, an elusive quantity at best. The quality-of-life index was calculated from a group of environmental quality indices derived from economic, social, political, and ecological sectors. Each of these indices was quantified according to its relative value to the community at large and was in turn related back to how it would be affected by land use allocation. The problem was treated at a regional level, and a realistic but hypothetical problem area was treated in lieu of a real-life study for want of time, data, and resources.

The problem of land use planning has received wide attention in the literature of late due to the heightened interest in ecological balance and to shortages of many of our resources previously taken for granted. Some examples of recent projects devoted to consideration of facets of land use planning are Hamilton *et al.* (1969), Forest-Range Task Force (1972), and Kaiser *et al.* (1972). International attention to man's use of his resources and interaction with the environment is reflected in the development of a coordinated MAB (Man and the Biosphere) programme as a sequel to the IBP (International Biological Program). In the United States considerable effort has gone into land use planning research via the RANN (Research Applied to National Needs) programmes of the National Science Foundation.

Looking at the land use planning problem from the standpoint of quality of life also has some basis in historical fact. Attempts at quantifying quality of life have come from a variety of disciplines and the subject has been the topic of frequent discussions in workshops and symposia. Papers relating to quantifying quality of life have been offered by Deevey (1971), Swartzman (1972), and Van Dyne and Innis (1972). The topic was treated at a symposium conducted by the American Association for the Advancement of Science (AAAS) at their national meeting in 1972. Recently, a series of abstracts has been published on regional modelling, many of which are concerned with economic, societal, ecological, and land use responses of a geographical region to alternative policy decisions (Meyers, 1971*a*, *b*, 1972).

The problem treated in the body of this paper was initially formulated and the solution methodology structured at a series of four monthly interval workshops concerning the application of optimization techniques to ecological management problems. These workshops were conducted in early 1971 under the auspices of the US/IBP Grassland Biome study in reviewing and planning approaches to utilization studies. Participants included professors and graduate students from the Colorado–Wyoming Rocky Mountain Front Range universities from a variety of disciplines ranging from political science to mathematics to range ecology (see Acknowledgments). Subsequently, the authors converted the conceptual and quantitative relationship from the workshops and interim efforts into a mathematical programming formulation presented herein.

The objective of this paper is to examine multidimensional decision making problems from a quantitative standpoint using a case example.

We recognize that communities are now being confronted with planning decisions of ever widening complexity and planning horizon. As man's censusing ability grows, he can delve further and further into the complexity of both the implementation and the effects of land use decisions. The systems are large and complex and multidimensional. Inputs must come from ecological, sociological, economic, and political experts. The decisions must be made with an imperfect data base and speculative knowledge of the effects of the decision. Furthermore, the evaluation of desirability of a particular policy is laden with *value judgment*—a difficult area to assess and one that has been fastidiously circumvented by the scientific community until recently through the use of dollar-laden arguments and other similar ploys. It is in the hope of bringing these problems to the forefront and providing a usable quantitative framework for community decision making that this paper has been written.

The actual problem devised and the particular quantitative curves presented here are only preliminary and represent our (the workshop participants') best estimates of a realistic community land use diorama. They are not offered as definitive and are certainly open to revision.

2. A case example

Decision making in resource management usually involves a great deal of study of the managed system before decisions are undertaken. Our interdisciplinary workshop group had neither the time nor the funding to undertake a full-scale study of a real region. However, we felt there are many common denominators in land use allocation decisions throughout the world. Therefore, we *devised* a case example for a typical western United States semiarid land area and decided to treat it as an area in which an intensive study had been undertaken and about which a great deal of information was available to aid in decisions about land development in that area. This problem is outlined in Figure 1.

As an initial structuring of the above problem, we desire a decision-making process which will tell how to allocate the land available in this area to combinations of various land use categories. For purposes of simplification, the following three land use categories were chosen: (i) urban, (ii) irrigated forage and food crop, and (iii) range.

We shall call the fraction of the total Riverton area denoted to each of these land uses *system variables* since they may be changed by the planner.

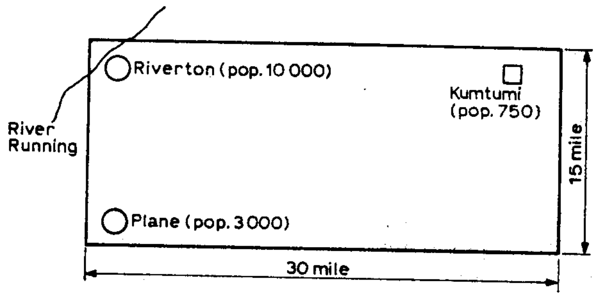

Figure 1. The " River Running " Problem. The river flows through the corner of a region in " Upper-Agraria " County (the real names have been changed to protect the area). Three towns are in the region. " Riverton " is a major distribution centre and lies in the rich agricultural belt irrigated from River Running. Average annual rainfall is 12 to 14 inches, and when not irrigated it supports shortgrass prairie and has been traditionally a ranch area (largely heavily grazed). Riverton's business leaders have been promoting industry in the region and have held out promises of development of a subterranean aquifer to supply water needs for industry and irrigation. They have met with resistance from local ranchers who, although they are making only a marginal living, swear by their lifestyle. It is expected that, if the new irrigation project is initiated, the tillable land range could be extended as far as Plane. Friction between business leaders and farmers and ranchers, as well as a concern over how growth in the area should be planned, has resulted in the formulation of a regional planning commission composed largely of business leaders, a few ranchers, and several professors from Riverton Community College.

We looked at the planning commission as trying to make that land allocation decision which would best improve the *quality of life* of the individuals living in this area after a realistic planning horizon of let us say ten years. With this in mind, the allocation would best try to satisfy the community needs of as many groups living in this area as possible and to balance off conflicting interests between the ranchers, farmers, and businessmen in the region. To decide what the quality of life means to the community, we tried to obtain variables or indicators which relate to the quality of life. These were divided into four sectors: ecological variables, economic variables, political variables, and sociocultural variables. These variables are termed *objective variables*, since they relate to the objective of the planners, which is to maximize quality of life in the next ten years.

The system variables will be denoted by A_i with $i = 1$ for urban land use, $i = 2$ for intensive tillage land, and $i = 3$ for range (extensive grazing) land. We have chosen 20 quality-of-life indicators labelled $X_{k,i}$, where k goes from 1 to 20 and i is the land use category. These 20 indicators are defined in Table 1.

In searching for a land allocation decision which best achieves our objectives, certain possibilities will be eliminated either because they are a physical impossibility or they represent a degeneration of quality of life in one sector which is so undesirable as to be considered unacceptable (no matter how beneficial gains in other sectors might be). The elimination of certain decisions due to such considerations are called decision *constraints*. These exist in most realistic decision problems. As an example of such a constraint, the word model specifies that the intensive water use area could extend only as far as Plane, which implies that approximately 40% of the area at the maximum could be put into irrigation and/or other intensive water use. This is a constraint on the system variables based on physical limitations in the problem statement.

Since the objectives of the decision maker relate to quality of life represented by the quality-of-life indicators $X_{k,i}$ and since the system variables manipulable by the planner are the A_i's or land use areas, there must be some way to relate the objective variables $X_{k,i}$ to the system variables. This is done through a series of curves predicting the effect of land allocation upon the quality-of-life indicators. These are curves of A_i *vs.* $X_{k,i}$ for each k and i. With these curves the objectives can be seen as a function of the system variables which, since these are controllable by the manager, indicate management's indirect control over quality of life.

Another task is the *value standardization*. After we have chosen quality-of-life indicators and shown how they are affected by varying the A_i's, we must be able to tell how much each of the indicators are worth in terms of overall quality of life. This involves value standardization curves converting the $X_{k,i}$'s which all have different units into standard variables having the same units to allow for comparison of the objective variables. These standardized quality-of-life indicator values are denoted by $V_{k,i}$.

A third task is to specify the *constraints* on the system and objective variables.

With the quality-of-life indicators value-standardized and related to land allocation A_i and with constraints specified, it should be possible to obtain a solution (if one exists) using an optimization technique—more specifically, one of the programming algorithms (linear, non-linear, or stochastic). In this case the problem turns out to be a non-linear programming problem due to the nonlinearity of many of the standardization and $X_{k,i}$ *vs.* A_i curves.

3. Procedure for obtaining predictor and standardization curves

The three tasks outlined in the preceding section are operationally extremely difficult. The producing of these curves required a great deal of reasoning and speculation by the specialists in each of the four sectors. There was a great deal of argument and debate about how important some of the indicators were as well as whether we had the right indicators. We limited

TABLE 1. Quality-of-life indicators, their definitions, and notational designations. The subscript denotes the type of land—urban, agriculture, or range

Variable	Definition and units	Notation
1. Income per capita	Average per capita income ($)	$X_{1,i}$; $1 = 1, 3$
2. Employment stability	Working age working (%)	$X_{2,i}$; $1 = 1, 3$
3. Net regional product change	Net regional product ($) change over 10-year period (%)	$X_{3,i}$; $1 = 1, 3$
4. Income distribution	Coefficient of variation in incomes (μ/σ)	$X_{4,i}$; $i = 1, 3$
5a. Ecological degradation index (urban)	$\frac{SO_2\text{(p.p.m.)} + \text{CO(p.p.m.)}/20}{2}$	$X_{5,1}$
5b. Agricultural ecological degradation index	Pesticide and herbicide concentration (% saturation/100)	$X_{5,2}$
5c. Range or ecological degradation index	1/range condition	$X_{5,3}$
6. Environmental quality index	Landscape or habitat diversity index—$\sum_1 p_i \ln (p_i) p_i$ = percent in habitat type i	$X_{6,i}$; $i = 1, 3$
7. Use of renewable resources	Total possible use of such renewable resources as hydro-electric power and water without making them non-renewable (%)	$X_{7,i}$; $i = 1, 3$
8. Annual use of non-renewable resources	Annual use of nonrenewable resources such as coal and oil in the urban area (%)	$X_{8,1}$
9. Man-initiated energy consumption	Ratio of man-controlled energy inputs (fossil fuels, etc.) to solar energy utilized (unitless)	$X_{9,i}$; $i = 1, 3$
10. Population size	Population density (people/mile^2)	$X_{10,i}$; $i = 1, 3$

11.	Social differentiation	Number of separable job categories for the area	$X_{11,i}$; $i = 1, 3$
12.	Cultural heterogeneity	Number of significantly different life styles in a community	$X_{12,i}$; $i = 1, 3$
13.	Social solidarity	Feeling of community solidarity inversely proportional to crime rates (1/crimes/1000 population/year)	$X_{13,i}$; $i = 1, 3$
14.	Information gap	Ability of social system decision makers to keep up with information change $G = \frac{1_\ddagger - R_\ddagger}{1_\ddagger}$ ($1_\ddagger$ = information turnover rate; $R_\ddagger$ = decision-making adaptation rate)	$X_{14,i}$; $i = 1, 3$
15.	Scope of government services (total area)	Number of areas of government services provided including education, police protection, sewage, streeting, building, etc.	$X_{15,1}$
16.	Uses of government services	Population utilizing services provided (%)	$X_{16,1}$
17.	Political participation	Legal age population voting (local election, %)	$X_{17,1}$
18.	Property tax base	Average base valuation for property taxes ($/capita)	$X_{18,1}$
19.	Political power advantage	Governing body composed of competitive elite as opposed to traditional elite (%)	$X_{19,1}$
20.	Dollar investment	Dollar investment per acre for development in land use i; Assumed constant ($/acre)	D_i; $i = 1, 3$

the number to 20 for logistic purposes—certainly many other candidates might be added to the ones we have chosen.

To produce the predictor curves we decided to initially adopt a qualitative quality of life, we initially gave just the range of value the indicator would have on the indicators. These effects are shown in Table 2.

As a measure of the relative importance of the various indicators to overall quality of life, we initially gave just the range of value the indicator would have on an arbitrary +10 to −10 scale. We had a great deal of difficulty reaching agreement across sectors, each individual rating his disciplines' indicators to be the most important! We ended up somewhat arbitrarily selecting the relative importances of some of the indicators. The relative value range of each of the quality-of-life indicators chosen in this fashion is also given in Table 2.

For each of the quality-of-life indicators $X_{k,i}$ *quantitative* curves were developed relating the $X_{k,i}$ to A_i or to other quality-of-life indicators. These were quantifications of the relationships expressed in Table 2. The equations for these curves are given in Table 3, while examples for six representative quality-of-life indicators are given in Figures 2(a) to 2(f).

4. Quantitative effect of land use upon quality-of-life indicators

4·1. EMPLOYMENT STABILITY (PERCENTAGE OF LABOR FORCE WORKING)

In the urban areas it is assumed that job stability, $X_{2,1}$, increases originally as urban size, A_1, increases because of the attraction of new industry which increases the number of jobs available; but then as immigration increases, a larger percentage of the population is unemployed (Figure 2(a)). Employment overall is quite high in the rural and range areas, and it is not clear that there is any effect upon job stability of changing the amount of acreage in the various land uses. In the agricultural area employment is assumed constant at 92%, whereas in the range area employment is assumed constant at 90%. We are open to any ideas about changes in job stability with changing acreages in agriculture or range, as these are tentative hypotheses.

4·2. ENVIRONMENTAL QUALITY INDEX

The environmental quality is measured by an information index based on the number and distribution of "habitats" in each of the land use types. It is a measure of habitat diversity. The diversity index is mathematically given by

$$-\sum_{j=1}^{n} P_j \ln (P_j)$$

where P_j is the fraction of area in habitat type j and n is the total number of habitats. The index increases with increasing environmental diversity. The curve for the change in agricultural environmental quality index $X_{6,2}$ as a result of changes in A_2 agricultural area is given in Figure 2(b).

An agricultural area habitat refers to a number of wildlife habitats. Increasing agricultural acreage through irrigation will initially increase the habitat diversity. This means that the environmental quality index will be increased. However, with increasing acreage in agriculture, the diversity will drop because the previous areas will be replaced by an area with large single-crop stands which are less diverse than the smaller crop areas. The smaller plots have a tendency toward larger diversity of types of agriculture which increases the habitat diversity.

Habitat diversity for the range area also refers to wildlife habitat diversity, while in the cities the quality index is the human habitat diversity measured by numbers of types of places for creation and recreation.

In small towns the diversity of structures is assumed to be rather low with the types of commercial, industrial, and residential establishments being fairly uniform and similar. As the size of the urban area grows, the diversity increases with different kinds of commercial industries coming in, ghettoes being formed, neighbourhoods being formed, architectural influences from areas playing a role, and different and varied kinds of commercial establishments being instituted.

It should be mentioned that these relationships represent only the general response of diversity to changes in the amount of acreage of the various land uses. Diversity indices found in the field lie mostly within the range of 1·5 to 4. We have actually done no studies to show that either habitat diversity or urban habitat diversity would fall in this range. Thus, this curve includes our inference or hypothesis about the diversity range.

4·3. PERCENTAGE ANNUAL USE OF NON-RENEWABLE RESOURCES

By non-renewable resources we refer to the resources such as oil and gas. We look at the average percentage of the remaining resources used per year over the 10-year time period. As an example of what utilization of non-renewable resources means, a 3% annual utilization of resources will result in 50% depletion of the resource stock in about 22 years.

Most of the non-renewable resources are not directly connected with a particular land use. They may occur in any one of the land use regions. The majority of non-renewable resources are used by the large population density areas. Thus, we are looking at the use of non-renewable resources for the entire region (called $X_{8,1}$), and we are considering the population

TABLE 2. Quality-of-life index variables in the economic, ecological, sociocultural, and political spheres. The subscript i refers to the type of land

Variable	Relative importance (value range in value units)	General influence of increase in variable on value	Effect of increasing land usage in		
			Urban	Agriculture	Range
Economic					
1. Income per capita, $X_{1,i}$	4	+	Increasing	Increasing	Increasing
2. Employment stability, $X_{2,i}$	16	+	Increasing	Increasing and then decreasing	Increasing and then decreasing
3. Net regional product change practice, $X_{3,i}$	20	+	Increasing	Increasing and then decreasing	Increasing
4. Income distribution, $X_{4,i}$	18	+ for low, − for high	Increasing and then decreasing	Constant	Constant
Ecological					
5. Ecological degradation, $X_{5,i}$	20	−	Increasing	Increasing	Increasing and then decreasing
6. Environmental quality index, $X_{6,i}$	11	+	Increasing	Increasing and then decreasing	Decreasing and then increasing
7. Percentage use of renewable resources, $X_{7,i}$	4	+ under 100, − over 100	Increasing	Increasing over 100	Increasing over 100 and then decreasing under 100
8. Annual percent usage of nonrenewable resources, $X_{8,i}$	14	−	Increasing	Not applicable	Not applicable