# SPATIAL ASPECTS OF DEVELOPMENT

Edited by B. S. HOYLE

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# of
# Development

*Edited by*
B. S. HOYLE

*Lecturer in Geography*
*University of Southampton*

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# *Foreword*

At a time when mankind is becoming increasingly aware of the limitations of his environment and when we must consider earnestly the ways and means at our disposal for the servicing and maintenance of our planet, a wide variety of specialised and interdisciplinary studies are being made in the field of development. In this context, contributions from geographers concerned with the understanding and eventual solution of development problems are particularly welcome. The spatial dimension is an important, basic framework within which considerations of developmental problems must be set; and contrasts between the problems of the less-developed countries and those of the advanced nations, both in environmental and socio-economic terms, require careful analysis. In these respects geographers who have lived and worked, often for many years, in the less-developed countries, have frequently made, and continue to make, important contributions.

The essays presented in this volume reflect both established traditions and new departures within the field of the geography of development. On the basis of original field work, methods of approach vary from synthetic description to analytical quantification and model-building. A basic objective throughout is to increase understanding of existing situations and to suggest new strategies which might be adopted in an effort to solve certain developmental problems. Varied ecological backgrounds, differences in history, society and culture, have led to rather widely varying perceptions on the part of governments, both in less-developed and in advanced countries, as to methods of attacking developmental problems. Geographical enquiry, while stressing this dual variety, may also help to illuminate interrelationships between contrasting areas of experience and activity.

It is important to stress repeatedly the significance to mankind of the less-developed world, perhaps especially the tropical areas where many ecosystems have a high biological productivity along with a great variety of animal and plant species. The trouble is that we still do not know enough about how such systems work to be able to manipulate and to tap their resources without destroying them. Conditions in tropical areas differ so markedly from those in temperate latitudes that we cannot just transfer

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## *Chapter 3*

# *Ecological Modelling of a Tropical Watershed: A Guide to Regional Planning*

*Gustavo A. Antonini, Katherine Carter Ewel and John J. Ewel*

### Introduction

Increased pressure on the limited resources of the earth make the study of resource depletion one of the most urgent needs of our society today. The study of man–environment relationships is imperative because the stress of human occupancy upon the biosphere has reached a critical stage. The need is particularly great in tropical regions, for it is there that population growth is most rapid and resource management is, in general, least technically developed. This chapter is concerned with the need to develop new geographical and predictive techniques to evaluate resource depletion in the tropics. As such, the chapter describes the application of time-sequential models as new tools for measuring the impact of past land-use changes on the physical landscape and predicting the resulting environmental consequences. The objective is to discuss these new methods which can assess quantitatively the productive potential and relative environmental stress of traditional exploitative tropical life-support systems, using the central Dominican Republic as a case study.

### Study region

The Dominican Republic is a microcosm of emerging nations, attempting to achieve accelerated economic development under the twin pressures of rapid population growth and rising per capita income. Though agriculture is the dominant economic sector, with 60 per cent of the total labour force,

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Dr. Gustavo Antonini is Associate Professor of Geography and Latin American Studies at the University of Florida, Gainesville, and is also Coordinator of Research for Latin American Studies at that institution. Dr. Katherine Ewel is associated with the Florida State Museum at the University of Florida. Dr. John Ewel is Assistant Professor of Botany at the University of Florida.

farm output accounts for only 24 per cent of the gross domestic product (Inter-American Development Bank, 1971, p. 192). To accelerate expansion of the farm sector, to achieve a more equitable income distribution and to stem the tide of rural migrants to the cities, the Dominican Republic has embarked upon a number of coordinated regional development programmes scheduled for completion under the government's National Development Plan for the 1971–74 period (ONAPLAN, 1970).

O greatest significance to the country's economic development is the construction of a series of hydroelectric power and water storage installations at Tavera on the Yaque del Norte River and near Sabana Iglesia on the Jagua River (SOGREAH, 1968; Lahmeyer International GMBH, 1967). Valued at US $60 million and scheduled for completion about 1975, this project will comprise a total installed power capacity of 135 000 kilowatts and in addition will sustain the irrigation requirements of a 400 $km^2$ tract downstream in the semi-arid but potentially fertile north-western region of the country (Antonini, 1972, p.253).

The ecological study described in this chapter covers the 407 $km^2$ area located upstream from the Jagua dam site. Since 1950, population has doubled in this mountainous region, yet agricultural productivity during the same period has declined. Furthermore, much of this upland, formerly in pine forest, has been subjected to slash-and-burn farming and extensive grazing (United Nations, 1971). These factors, juxtaposed with the cessation of lumbering operations in 1967, have produced an out-migration of some 4000 labourers, principally to New York City.

In this populated upland region, the links between man and nature are so direct that clearly the continued practice of marginal farming and illegal logging will cause increased erosion of the soil and depletion of the region's resource base. Increased demand for downstream irrigation water requires that sedimentation be halted and erosion controlled. The ecological incompatibilities arise because the more intense the land use the greater the hazard from erosion and siltation.

## Modelling procedures

To study and evaluate the dynamic interplay between man and the land, the geographer must be able to integrate the virtual infinitude of variables and attributes of the natural landscape with the cultural features of evolving land use. Fortunately, these are not haphazardly arranged, but are organised into man-land ecosystems in which agents, materials and processes are intimately related in well-defined geographical patterns. Each land-use system is a man-managed activity that is fitted with varying degrees of conformity to the physical resource base. Departures of land-use systems from the natural order are due to cultural investments. In this study, a technique was required to examine those systematically related natural variables and cultural landscape features that are functionally involved in land use and which affect ecological balance in the region. Energy flow modelling (Odum, 1969 and 1971) was used as the integrating mechanism for evaluating cause-effect relationships in the watershed area between evolving land use and ecological change.

All systems carry on energy transfer processes. Similarly, energy flow is a common denominator which can be used to unite interactions of all kinds. All viable systems maintain energy flow through themselves and culturally determined systems are no exception to this rule. In the Jagua–Bao region, man's relationship to the land is a fairly direct one in which the population is almost entirely dependent upon local energy sources—sun, water, available nutrients—rather than energy derived from fossil fuels. Consequently, the feedback processes between man and the land are direct and the total population that can be sustained in a given community depends almost entirely on their direct relationship to the land. The construction of the Jagua dam is an additional constraint within the ecological system since the viability of the hydropower facilities is dependent on the management practices in the upper watershed which in turn affect the hydrological characteristics of the basin itself. Modelling was used to relate present population growth patterns and evolving land-use practices to their corresponding effects on the dam over the 1945–2015 year period.

Two models were developed. First, a land-use model was established to examine the relationship between population growth and conversions of forest to various classes of agricultural use. Second, a water balance model was used to examine rates of runoff produced by the temperature and rainfall régimes in the area under different soil characteristics. The final analysis integrated the two models by imposing different runoff coefficients on each of the land-use practices to quantify the effects of evolving land-use patterns on future siltation in the downstream reservoir.

The modelling process entailed the following sequence of steps: (1) construction of an energy flow diagram; (2) determination of flows and transfer coefficients; (3) conversion of the energy flow diagram to a set of differential equations; (4) scaling and analog computer programming of the differential equations, according to standard procedures (see, for example, Peterson, 1967); and (5) simulation on the analog computer. Throughout the process, the analog computer was used because a variety of simulations can be explored almost immediately and communication between the computer and the modeller is nearly instantaneous. The models described could, however, have been simulated equally well using digital computers.

## Data base

Owing to the size and scope of the study, various data collection techniques were employed. The general lack of published documentary material on contemporary land use required that heavy reliance be placed on extensive personal interviews with local inhabitants as a primary research method in reconstructing the cultural fabric of daily and yearly activities.

**Table 3.1** Categories of information obtained by field interviews

- I Classification of administrative (mapping) units
- II Population
  - A. Census
  - B. Labour force
  - C. Internal/external migration
- III Land-use activities
  - A. Farming
  - B. Grazing
  - C. Logging
  - D. Other activities
  - E. Historical land-use information
- IV Land tenure
  - A. Nature and scope of rights in land
  - B. Owned land
  - C. Sharecropped land
  - D. Common (squatted) land
- V Transportation
  - A. Trafficability
  - B. Road maintenance
  - C. Mode of transportation
- VI Diet
  - A. Food consumption
  - B. Imported foods
- VII Vegetation changes
  - A. Types
  - B. Reasons
- VIII Local energy sources
  - A. Functions
  - B. Types and consumption of fossil fuels
- IX Mass Media and education
  - A. Newspapers and periodicals
  - B. Education

Interviewing was performed during the summer of 1971 and the sampling procedure was structured to obtain cultural data from all twenty-one settlements at the smallest definable territorial level. Categories of information obtained by field interviewing are presented in Table 3.1. The interview schedule classified differences in the spatial arrangement of human activities based on cultural and physical elements of the settlement's resource base.

Another primary source of information on changing land use was aerial photography available for the years 1948, 1958 and 1966. The three sets of photographs were examined under stereoscopy and land-use maps were compiled at a 1:50 000 scale. For each map four basic categories were delineated: forest, pasture, short-cycle mixed farming and coffee. Where photo-scale precluded identification of individual units, combinations of the basic divisions were plotted using a ratio of major to minor land use (e.g. forest greater than pasture, 70 per cent forest and 30 per cent pasture). Next, composite land-use change maps were compiled for the years 1948–58 and 1958–66. These maps indicated the change in land use for any given area of the study region. The purpose of this map compilation phase was to establish a basis for planimetering land-use areas in each time dimension and obtaining transfer coefficients of land-use change between the various mapped units for later model simulation. Table 3.2 is a summary of map measurements for total area under forest, pasture, mixed farming and coffee for the 1948, 1958 and 1966 periods.

**Table 3.2** Summary of map measurements for total area under forest, pasture, mixed farms and coffee for the 1948, 1958 and 1966 periods

| | | Area | |
|---|---|---|---|
| Land use | 1948 km$^2$ | 1958 km$^2$ | 1966 km$^2$ |
| Forest | 227 | 172 | 147 |
| Pasture | 98 | 119 | 163 |
| Mixed farming | 60 | 82 | 69 |
| Coffee | 22 | 34 | 28 |
| Total area | 407 | 407 | 407 |

## LAND-USE MODEL

The energy flow diagram of the land-use model is shown in Figure 3.1. Population is represented by the hexagon. This symbol, denoting a self-maintaining consumer, has inputs from outside subsidies and agricultural production, and outputs expressed as agricultural work (farming, animal husbandry, land clearance), as well as losses which include death and emigration. The lines indicating losses from the population and energy expended in agricultural tasks, as well as forest clearing, flow into arrow-shaped rectangles called work gates. These work gates imply that one energy flow interacts with a second, in such a way that the first permits the second to occur and magnifies (in a manner often assumed to be multiplicative) its effect. The work gate is similar to the triangular symbol, called a 'constant gain amplifier'. In this case, however, the rate of flow from one component increases the rate of flow from another by some constant factor, while not constituting a significant energy drain on the first component. In Figure 3.1, the interaction of various amounts of agricultural land with environmental energy sources (e.g. sun, water, nutrients) is an example of the use of the constant gain amplifier. The amount of crops that can be produced is proportional to the amount of land cultivated, provided that the necessary factors for growth of the crops are present.

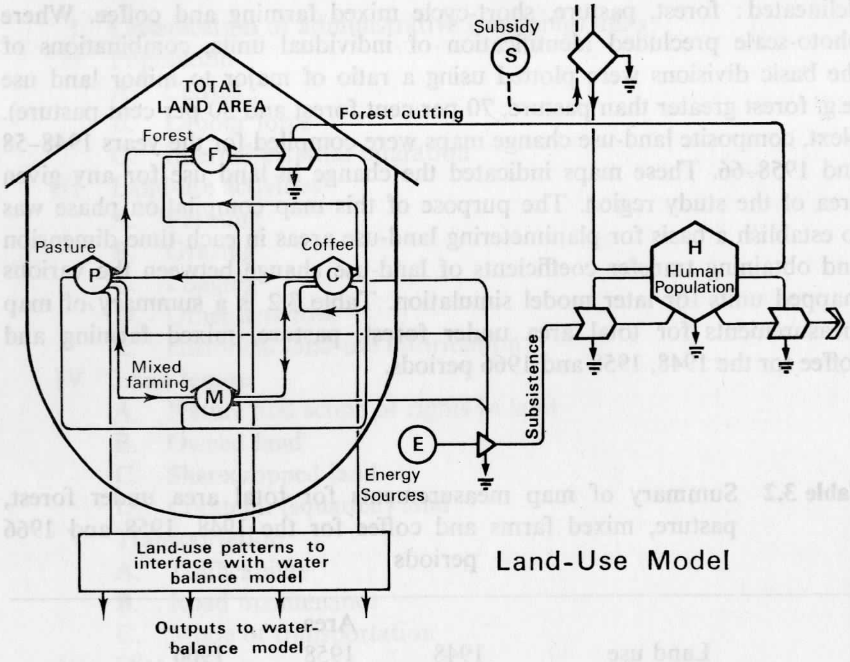

**Figure 3.1** Energy-flow model of land-use pattern and population growth in the Jagua–Bao watershed (symbols after Odum, 1969 and 1971)

Two circles are shown on the diagram, one labelled 'energy sources' and the other labelled 'subsidy'. The energy circle is generally used to represent energy from outside the system of immediate interest and implies the presence of a continually available forcing function. Solar energy, mineral nutrients and rainfall are examples of possible energy sources. The subsidy circle represents money (or its energy equivalent) sent into the area by emigrants for their families. The flow of money (shown by a dashed line) from this outside subsidy is shown to pass through a diamond-shaped symbol, called an economic transactor, which indicates the exchange of money for an equivalent energy flow.

The left-hand side of Figure 3.1 shows a large tank-shaped symbol (passive energy storage) containing four smaller storage symbols labelled 'forest', 'coffee', 'pasture' and 'mixed farming'. Each storage represents the area devoted to each land use at any given time. Their enclosure within the larger storage symbol, labelled 'total land area', implies that the sum of the four land-use storages is constant. This is believed to be the first application of such an areal constraint within the context of the energy flow language, a factor which enhances the technique's adaptation to problems of regional analysis.

In the model land is removed from forest through man's overt action. It can become farmland, a coffee plantation or pasture. Likewise, as land is abandoned, flows are shown going from each agricultural land use back into forest. In addition, any of the three agricultural land units is interconvertible with any other. This should be drawn as two lines—an input and an output—connecting each one of the three to the others, but, because of the confusion which results from so many lines, each of these transfers is shown as a single line with arrows pointing in both directions. This should not, however, be interpreted as implying that the rates of flow are the same in both directions.

At the lower left-hand side of Figure 3.1 is a box labelled 'land-use patterns to interface with water-balance model'. What is indicated here is that the area in each land unit was entered as a variable into the water-balance model used ultimately to predict sedimentation rates.

The differential equations which express the rates of change of each component shown in Figure 3.1 are:

$$\begin{aligned}
\mathrm{d}H/\mathrm{d}t &= k_1 (k_2M + k_3P + k_4C)\, H + k_5SH - k_6H - k_7H^2 \\
\mathrm{d}F/\mathrm{d}t &= k_8K + k_9P + k_{10}C - k_{11}FH \\
\mathrm{d}C/\mathrm{d}t &= k_{12}FH + k_{13}M + k_{14}P - k_{15}C \\
\mathrm{d}P/\mathrm{d}t &= k_{16}FH + k_{17}M + k_{18}C - k_{19}P
\end{aligned}$$

where k represents various transfer coefficients and flow constants, discussed below, and

$H$ = human population
$P$ = land in pasture
$F$ = land in forest
$C$ = land in coffee
M = land in mixed farming = total land area − ($P$ $F$ $C$)
$S$ = subsidy sent by emigrants to families residing in the region

### Calculation of rates

The rates of change between the various land-use categories are shown in Table 3.3. The total loss from each compartment is shown, as well as the partitioning of the loss to each of the other land uses. These are the transfer coefficients derived from the planimetered areal measurements off the composite land-use change maps, described earlier. The flows into and out of the population component of the model are flows of energy, those leading from the three producing land-use categories—mixed farming, coffee and pasture—through the constant gain amplifier representing the energy yield from each of the land units. Energy flow from each land-use category was evaluated according to the following standard procedure.

**Table 3.3** Rates of land use change per year, averaged over 18 years. Values represent per cent change per year and each one corresponds to a coefficient in the land-use model

| | | To | | | | |
|---|---|---|---|---|---|---|
| | | Forest | Pasture | Mixed farming | Coffee | Total loss |
| From | Forest | — | $k_{16}$:2·26 | 0·91 | $k_{12}$:0·36 | $k_{11}$:3·53 |
| | Pasture | $k_9$:2·58 | — | 2·78 | $k_{14}$:0·68 | $k_{19}$:6·04 |
| | Mixed farming | $k_8$:1·83 | $k_{17}$:5·17 | — | $k_{13}$:1·57 | 8·57 |
| | Coffee | $k_{10}$:2·22 | $k_{18}$:3·45 | 3·10 | — | $k_{15}$:8·77 |

To calculate the energy flow from mixed farming, the total yield per unit area of each crop was determined from interview schedules conducted in the region. Yield was converted to an equivalent caloric value of 2·7 kilocalories (kcal) per gram of edible material; this value was derived by averaging the caloric values, according to Wu Leung and Flores (1961), of each crop grown in the study area. Poultry production was included in the mixed farm production estimate; 4·5 kcal g$^{-1}$ (Golley, 1961) was used as the conversion factor for the meat. A net rate of 8·45 x 10$^6$ kcal ha$^{-1}$ year$^{-1}$ was calculated for this flow.

The net yield of meat, primarily beef, was calculated similarly, using the conversion factor of 4·5 kcal g$^{-1}$. This value was about an order of magnitude less than that of crops: 6·53 x 10$^5$ kcal ha$^{-1}$ year$^{-1}$. Coffee has little caloric value itself, yet the return of dollars for its sale represents a fairly sizeable income. Therefore, the amount of money which was exchanged for coffee was converted to an equivalent number of kilocalories. To do this, it was assumed first that money earned from the sale of cash crops produced is normally exchanged for an equivalent caloric input and, second, that in a non-fossil-fuel economy money can be used as barter in the exchange of energetic inputs and outputs. A day's work should therefore bring a wage allowing a day's subsistence. Similarly, money earned from the sale of meat should accordingly be exchanged for an equivalent number of calories of another necessary food item, or for items such as clothing or farm implements which would facilitate the production of an equivalent amount of food. By dividing the average caloric value of crops by the average price received for them at market, the value of one dollar was calculated to be worth approximately 13 000 kcal. This value is similar to the conversion rate of 10 000 kcal to the dollar determined independently by Odum (1967) for a fossil-fuel-based economy. The net yield of coffee, on this basis, was 3·17 x 10$^5$ kcal ha$^{-1}$ year$^{-1}$.

Information gleaned from the interviews indicated that about one-third of the total population, primarily men, were engaged in some type of agricultural activity. A daily expenditure of 2000 kcal per person was estimated for these workers. Additional seasonal inputs of women and children in the harvesting of coffee were also included. The expenditure of labour for each type of agricultural activity was subtracted from the yield to give a net flow of energy into the population. The labour involved in agricultural activity included cutting down the forest, even though it is shown on the diagram as a separate flow.

The return of money to the Jagua–Bao region from emigrants was a very significant input in a number of the communities. However, it was discovered during earlier simulations that the energy returning in the form of dollars essentially compensated for the loss of energy by the emigration process itself; these rates were therefore included in the remaining net inputs and outputs of the population component. Because not all vital statistics were known, the coefficients used to describe changes in the population, $k_1$, $k_5$, $k_6$ and $k_7$, differed slightly from those calculated. The model demonstrated very early, for example, that the doubling of the population between 1950 and 1970 was a rate which could not be sustained for very long. The physical resources of the Jagua–Bao region, according to the land-use model, would not even remotely be capable of maintaining that kind of continued population increase without massively increased subsidies from outside the basin. Therefore, the population curve was programmed in such a way that the growth rate decreases in time, although the population itself is still increasing in the year 2015. In this sense, the model is optimistic with regard to future population trends within the region.

## WATER BALANCE MODEL

Land management practices within the watershed are intimately related to the usefulness of the downstream reservoir; the two systems, land and water use, are so tightly coupled as to be inseparable. However, unlike the evolving patterns of land use, data on the water inputs and outputs to the watershed, as well as the effects of land use on these flows, were not readily available.

Given accurate data on soil characteristics, total rainfall inputs, storm intensities, storm frequencies, slope, ground cover and stream channel morphology, hydrologists can predict with great accuracy the runoff and sediment loads likely to occur from a watershed. For example, the series of studies edited by Pereira (1962) are excellent examples of detailed hydrological studies on tropical-based watersheds. Very often, however, as was the case in the Jagua–Bao region, the data required for a detailed accurate analysis of the relationship of land use to runoff and sedimentation are lacking. In such cases, regional planners can choose (1) to abandon the problem as being insoluble; (2) to suggest, optimistically, that the development project should stop while they gather their ten-year baseline data on soils, runoff and rainfall inputs; or (3) to proceed to make the best estimates possible based on available information and general relationships among climate, land use and hydrology. Aware of its limitations, but dismayed by the alternatives, the latter approach was chosen.

The purpose of this phase in the analysis was to develop a water-balance model, compatible with the land-use model, to permit coupled simulation and utilisation of the limited available watershed data to the fullest extent possible. To achieve this end, the energy flow language was adapted to Tosi's (1968, 1971) method of calculating water balances, which in turn is closely linked to the Holdridge life zone classification (1947, 1967; Holdridge *et al.*, 1971). A life-zone map of the Dominican Republic (Tasaico, 1967) made this a particularly useful starting point for moisture budgeting within the Jagua–Bao region. Tosi's water balance calculations are keyed to Holdridge's (1959) assumption regarding the linear relationship between potential evapotranspiration and biotemperature, biotemperature being the average temperature calculated by the substitution of 0 for values below 0 °C and, tentatively, above 30 °C. The calculation of water balances usually involves the construction of an input–output budget table, with an entry for each variable each month. Rather than divide the year into a series of discrete months, however, it was necessary to express the water régime as a continuous flow process. Thus, Tosi's method was translated first into the energy flow language and then into the water balance model shown in Figure 3.2.

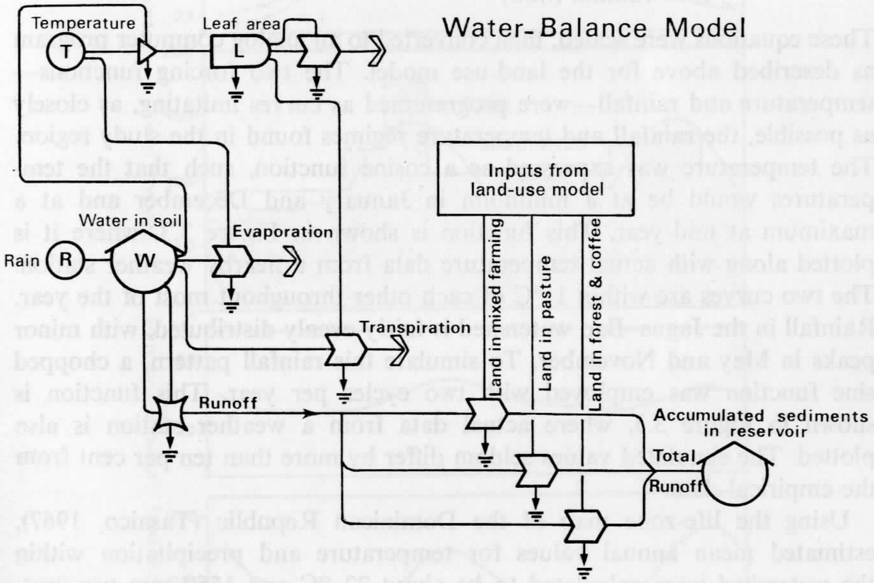

**Figure 3.2** Energy-flow model of water budget and sediment accumulation in the Jagua–Bao watershed (symbols after Odum, 1969 and 1971)

This model has two variable forcing functions: temperature and rainfall. Rainfall is the input to soil moisture, from which water can be lost either as evaporation (controlled by temperature), transpiration (controlled by leaf area) or runoff. The switching mechanism controlling runoff prevents this loss until the amount of water in the soil exceeds field capacity. Leaf area, the area of leaf surface per area of soil surface, is affected by the interaction of soil moisture and temperature and has a loss term which increases as the square of the leaf area present. Two flows shown in Figure 3.2 are assumed to be critical to certain processes, but are insignificantly small when considered as drains on the storages from which they originate. These two flows—the metabolic water involved in plant growth and the cost of transpiration to the leaf area component—do not appear as loss terms in the differential equations. The equations which express the relationship shown in Figure 3.2 are:

$$dL/dt = k_{20}TLW - k_{21}L^2$$

$$dW/dt = R - W(k_{22}T + k_{23}L) - \text{runoff}$$

where runoff $= W - (W(k_{22}T + k_{23}L) + \text{field capacity})$

$L$ = leaf area (area of leaf surface per area of soil surface)

$T$ = temperature (°C)

$W$ = water in soil (mm)

$R$ = rainfall (mm)

These equations were scaled, then converted to an analog computer program as described above for the land-use model. The two forcing functions—temperature and rainfall—were programmed as curves imitating, as closely as possible, the rainfall and temperature régimes found in the study region. The temperature was expressed as a cosine function, such that the temperatures would be at a minimum in January and December and at a maximum at mid-year. This function is shown in Figure 3.3, where it is plotted along with actual temperature data from a nearby weather station. The two curves are within 1 °C of each other throughout most of the year. Rainfall in the Jagua–Bao watershed is fairly evenly distributed, with minor peaks in May and November. To simulate this rainfall pattern, a chopped sine function was employed with two cycles per year. This function is shown in Figure 3.3, where actual data from a weather station is also plotted. The simulated values seldom differ by more than ten per cent from the empirical data.

Using the life-zone map of the Dominican Republic (Tasaico, 1967), estimated mean annual values for temperature and precipitation within the watershed were calculated to be about 22 °C and 1550 mm per year, respectively. The magnitude of each of the forcing functions was set to produce these values for temperature and rainfall. Because of the moderately high elevation of the basin, it was not necessary to correct temperature data for differences between air temperature and biotemperature. Above elevations of about 250 m at the latitude of the Dominican Republic, air temperature can be taken as approximately equivalent to biotemperature (J. Ewel and Whitmore, unpublished).

Another parameter which exerts considerable influence on water balance is the water-holding capacity of the soil. Based on the known parent material, topography and geomorphology of the study region, an attempt was made to characterise a single 'most typical' soil for the entire watershed. The Las Piedras Puerto Rican Soil Series was selected as being a soil for which physical characteristics were available and which was apparently very similar to the principal soils found within the Jagua–Bao region. Using the data of Lugo-López (1953), field capacity of this soil was calculated to be 147 mm, assuming an effective depth of one metre. The model was run for a simulated one-year period and the results of that simulation are shown in Figure 3.3. The temperature and rainfall simulations were discussed above: evapotranspiration (i.e. evaporation +

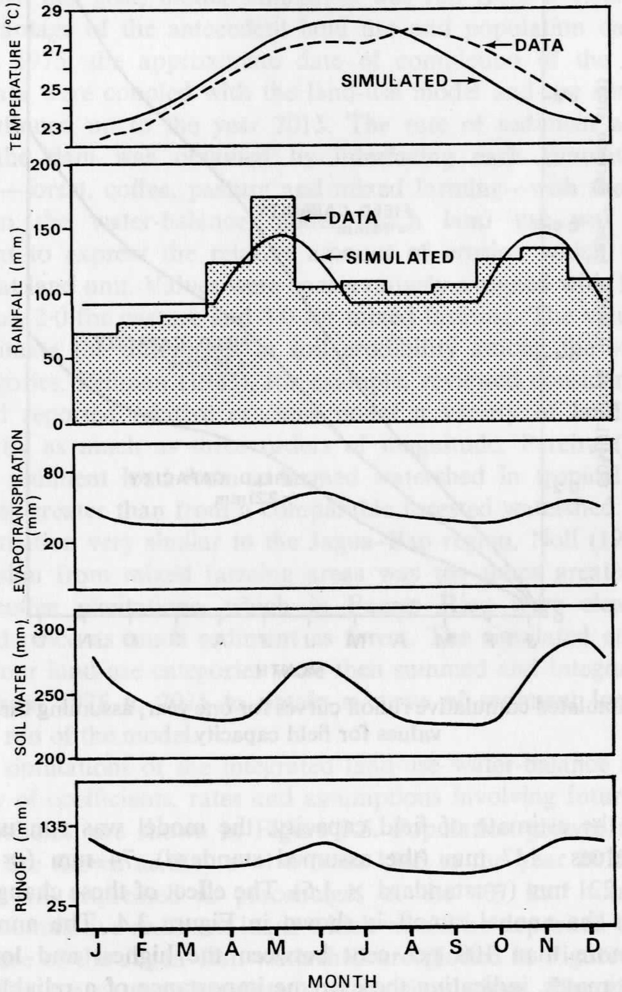

**Figure 3.3** Simulation outputs of water balance model for one year

transpiration), water in the soil and runoff all show two peaks during the year, as would be expected with a bimodal rainfall distribution. Soil-moisture recharge lags behind rainfall, indicating that runoff only occurs after evapotranspiration needs have been met and the soil is recharged to field capacity. Cumulative runoff during the simulated one-year period was obtained by integrating the continuous runoff data. To evaluate the effect

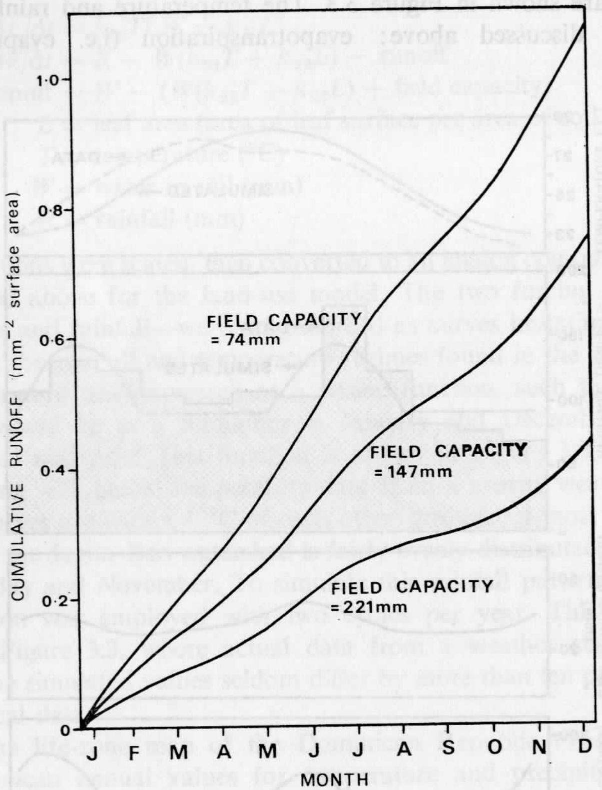

**Figure 3.4** Simulated cumulative runoff curves for one year, assuming three different values for field capacity

of varying the estimate of field capacity, the model was run using three different values: 147 mm (the assumed standard), 74 mm (= standard × 0·5) and 221 mm (= standard × 1·5). The effect of these changes in field capacity on the annual runoff is shown in Figure 3.4. The annual totals differ by more than 100 per cent between the highest and lowest field capacity estimates, indicating the extreme importance of a reliable measure of soil water holding capacity for an accurate prediction of runoff. In subsequent simulations, the intermediate, and assumed standard, value of 147 mm was used.

## INTEGRATED LAND-USE – WATER-BALANCE MODEL SIMULATIONS

The empirical land-use model and the water-balance model based on extrapolated data were integrated to examine the interaction of changing land use on runoff and sediment accumulation in the downstream reservoir. To achieve this goal, model simulation was run from a 1945 baseline to take advantage of the antecedent land use and population data from the area. At 1975, the approximate date of completion of the Jagua dam, runoff data were coupled with the land-use model and the simulation was then continued up to the year 2015. The rate of sediment accumulation behind the dam was obtained by interfacing each simulated land-use category—forest, coffee, pasture and mixed farming—with the runoff output from the water-balance model. Each land use was assigned a coefficient to express the relative amount of erosion which might occur under that land unit. Values were conservatively assigned with 1·0 for forest and coffee, 2·0 for pasture and 3·0 for mixed farming. The values probably underestimate the differences in soil erodibility among the various land-use categories. Penman (1963), for example, reviewed considerable erosion data and reported relative erosions under a variety of land uses which differed by as much as three orders of magnitude. Pereira (1962) found that the sediment load from a farmed watershed in tropical Africa was four times greater than from a comparable forested watershed. In a Puerto Rican situation very similar to the Jagua–Bao region, Noll (1953) reported that erosion from mixed farming areas was ten times greater than from forest; coffee plantations, which in Puerto Rico were clean-cultivated, produced twice as much sediment as forest. The simulated erosion values for the four land-use categories were then summed and integrated over the period from 1975 to 2015 to obtain a curve of sediment load over time for each run of the model.

Eight simulations of the integrated land-use–water-balance model, using a variety of coefficients, rates and assumptions involving future trends and public policies, are shown in Figure 3.5. Population growth and land-use changes are shown as they evolve from 1945 to the year 2015; changes in land use are expressed as percentages of the 407 km² total area. The relative cumulative sediment loads which would be deposited in a reservoir at the base of the Jagua–Bao watershed are plotted in Figure 3.6 for each of the land-use patterns predicted by the simulations. The topmost curve (line 'A') is the accumulation of sediments that would result if all land

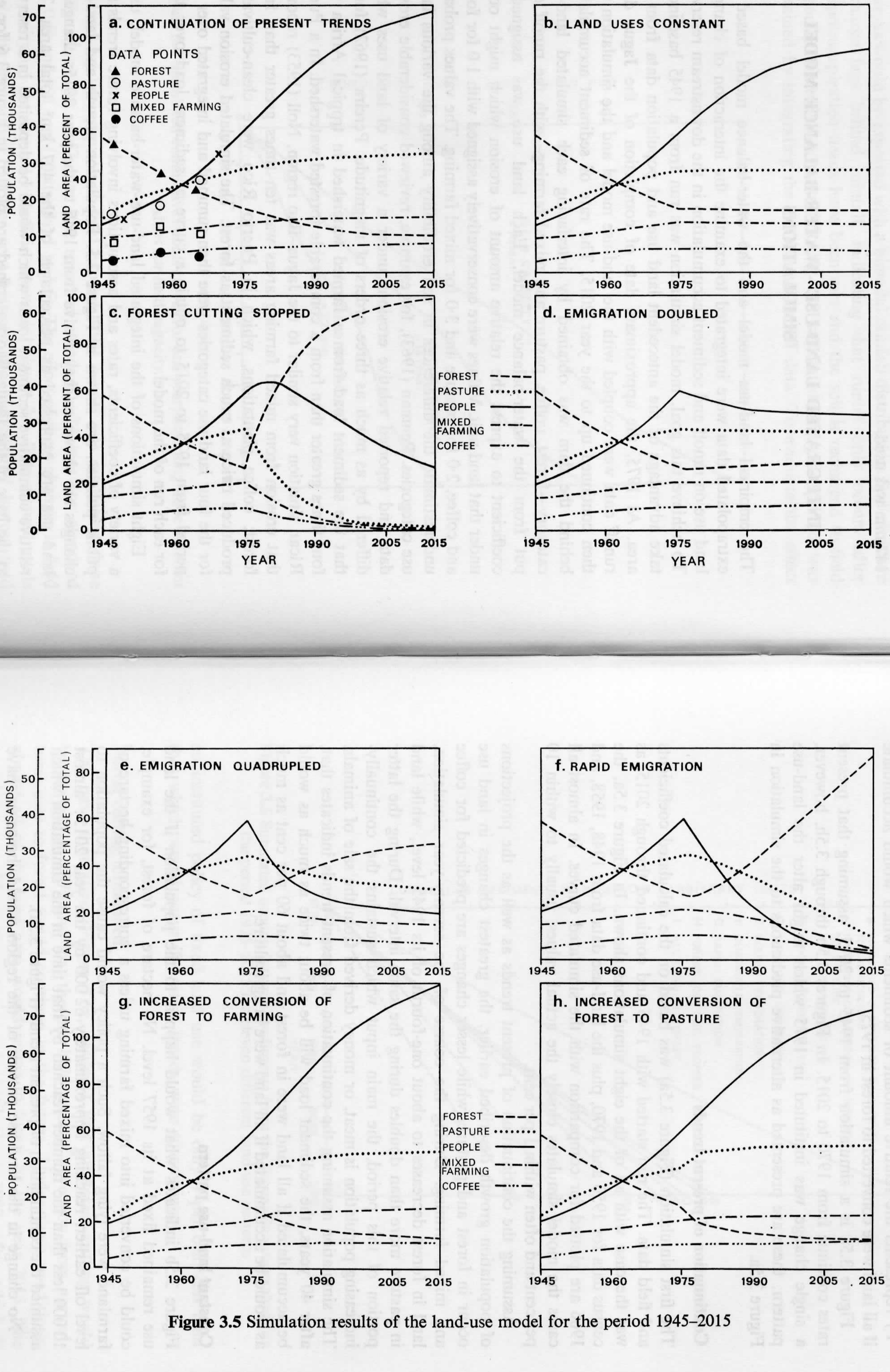

Figure 3.5 Simulation results of the land-use model for the period 1945–2015

were immediately put into mixed farming in 1975; the lowest curve (line 'I') represents the relative amount of sediments which would accumulate if all land were converted to forest in 1975.

Figure 3.5a is a simulation from 1945 to 2015, assuming that present rates continue from 1970 to 2015. In Figures 3.5b through 3.5h, however, a single change was instituted in 1975 which might alter the land-use pattern; these are presented as alternative predictions to the simulation in Figure 3.5a.

### Continuation of present trends

The first simulation (Figure 3.5a) was based on the calculated coefficients and field data. The run started with 1945 and continued through 2015, as was the case with all of the eight simulations shown. In Figure 3.5a, the census data for 1950 and 1970, plus the land-use data from 1948, 1958, and 1966 are plotted for comparison with the simulated curves. In almost all cases the model simulates closely the actual values, usually to within 10 per cent and often within 1 per cent.

Assuming the continuation of present trends as well as the projections of population growth described earlier, the greatest changes in land use occur in forest and pasture, while lesser changes are predicted for coffee and mixed farming. During the course of the seventy-year simulation, land in forest decreases to about one-fourth of its 1945 level, while land in pasture more than doubles during the same interval. During the latter portion of this period, the main input which sustains the continually-increasing population is meat, or money derived from the sale of animals. The simulation assuming the continuation of present trends indicates that, after 40 years, the sediment load will be about twice as much as would be accumulated if all land were in forest and about 60 per cent as much as would be accumulated if all land were in agriculture.

### Constant land-use pattern

Figure 3.5b indicates what would happen to the population if the land use remained fixed at its 1957 level. No hectare of forest, for example, could be converted into mixed farming unless a corresponding hectare of farmland were lying fallow. Such a policy would cause the population to level off earlier, reaching approximately 62 000 by the year 2015: almost 10 000 less than the number reached by that time in the simulation which assumed the continuation of present trends (Figure 3.5a).

No change in the land-use pattern of the region would, however, have very little effect on the accumulated sediments in the reservoir (Figure 3.6, line 'D'). By the year 2015, the predicted sediment accumulation under an instituted policy of fixed land use would be only 4 per cent less than that which would occur if present trends were to continue.

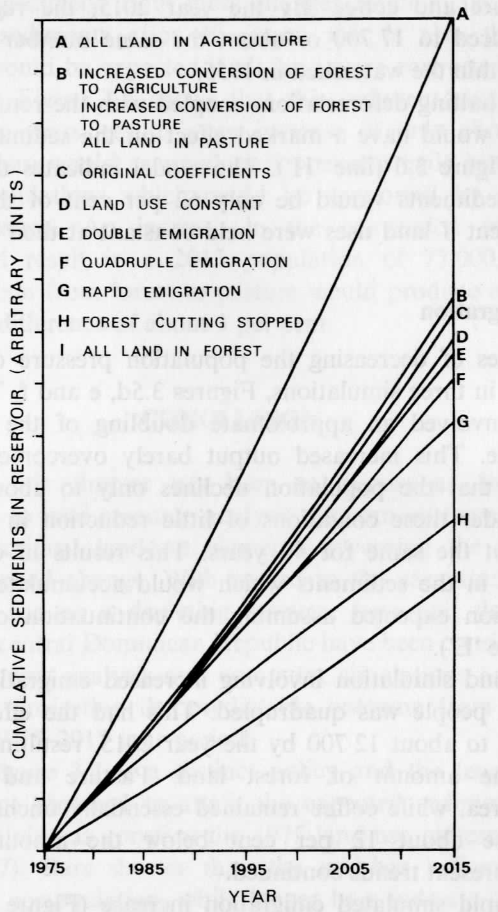

**Figure 3.6** Simulated accumulation of sediments from the Jagua–Bao watershed for the period 1975–2015 for eleven different land-use patterns

### Forest cutting terminated

The next simulation, Figure 3.5c, assumed that all forest cutting would be stopped in 1975 and that the pre-1975 rates of reversion from agricultural uses to forest would continue in the future. Under these conditions, almost all of the land area would revert to forest by the year 2015. The population would continue to increase until about 1982, after which it would begin to decline due to the reduced amount of land available for farming, pasture and coffee. By the year 2015, the region's population would be reduced to 17 700 or about the same number of people which were settled within the watershed in 1955.

A policy of halting deforestation, coupled with the return of agricultural land to forest, would have a marked effect on the sediment accumulation, as shown in Figure 3.6 (line 'H'). The model indicates that, by 2015, the accumulated sediments would be only 62 per cent of the amount which would be present if land uses were held constant at their 1975 levels.

### Increased emigration

The possibilities of decreasing the population pressure on the watershed were explored in three simulations, Figures 3.5d, e and f. The first of these, Figure 3.5d, involved an approximate doubling of the present regional emigration rate. This increased output barely overcomes the population expansion, so that the population declines only to about 31 000 by the year 2015. Under these conditions of little reduction in population, land use stays about the same for 40 years. This results in only a seven per cent reduction in the sediments which would accumulate, compared with the accumulation expected assuming the continuation of present trends (Figure 3.6, line 'E').

For the second simulation involving increased emigration (Figure 3.5e), the outflow of people was quadrupled. This had the effect of decreasing the population to about 12 700 by the year 2015, resulting in a significant increase in the amount of forest land. Pasture and mixed farming decreased in area, while coffee remained essentially unchanged. Sediments would decrease about 12 per cent below the amount which would accumulate if present trends continued.

The most rapid simulated emigration increase (Figure 3.5f) resulted in less than 1000 people remaining within the region by the year 2015. In this case, all agricultural land use decreases as a result of the population decline and most of the land reverts to forest. The resulting sediment accumulation after forty years (Figure 3.6, line 'G') would be only 81 per cent of that which would result from the continuation of present trends. This is still greater, however, than the sediment accumulation which would result if forest cutting were curtailed in 1975 and present rates of reversion from coffee, pasture and farmland to forest were to continue (Figure 3.6, line 'H').

### Modified land-use trends

Two final simulations involved increases in the rate of conversion from forest to mixed farming, and from forest to pasture, shown in Figures 3.5g and 3.5h respectively. Both these changes result in the same amount of accumulated sediments after 40 years; this is also the amount of sediment which would be expected if all land were converted to pasture in 1975. Line 'B' in Figure 3.6 shows that this sediment accumulation rate would, after forty years, result in an increase of only about 3 per cent more sediments than would accumulate if present trends were to continue. However, the populations which could be supported by each of these changes are different. An increase in the conversion from forest to agriculture would result in a 2015 population of 77 000, whereas the increased conversion from forest to pasture would produce a 2015 population of 75 000: a difference of about 3 per cent.

## CONCLUSION

The purpose of this chapter has been to discuss an interdisciplinary systems approach to land resource analysis that can evaluate the feasibility of manipulating critical land-use elements governing the ecosystem for programming planned change. With regard to the case study, the impact of evolving land use on a depleting resource base and the longevity of a reservoir in the central Dominican Republic have been considered. Specific results of the systems analysis and computer simulations are summarised in Figure 3.7 by projecting the predictable outcome from eleven public policies over the 1975–2015 year period.

Each bar in Figure 3.7 is a distinct policy and the length of the bar represents the time required to attain the expected sediment load in the year 2015, maintaining as constant the 1975 land-use pattern (see the mid-bar in Figure 3.7). Bars shorter than the mid-bar indicate more rapid rates of sediment accumulation, while longer bars indicate slower rates of sedimentation. Over a wide range of land management policies, the time required for each to reach the same sediment load differs by less than 10 years. The conversion of all land to mixed farming results in a decrease in time required to reach the standard sediment load by about 15 years, while curtailing deforestation and conversion of all land to forest in the year 1975 increases the time to reach that sediment load by 29 and 44 years respectively. Because of the conservative relative erosion rates assigned to each of the land-use categories in the integrated model, Figure 3.7 should represent *minimal* differences to be expected as a result of instituting one of a variety of land management decisions within the Jagua–Bao basin.

Energy flow models have been used to make an assessment of changes in the physical environment as a result of increasing population pressure over time, to evaluate the effects of these trends on evolutionary changes

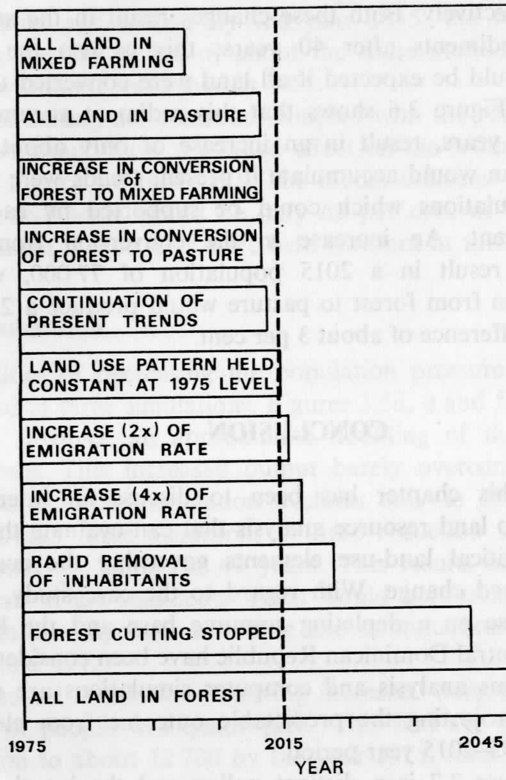

**Figure 3.7** Time required for various land-use patterns to produce the same cumulative sediment load that would be produced in 40 years under conditions of no future change in the 1975 land-use pattern

of forest lands and to obtain insights into the central problem of the relation between tropical environment and resource depletion. In this latter case, modelling and computer simulation have generated predictable outcomes for alternative public policies which can help avert erosion and control sedimentation.

Ecological similarities with other tropical regions make possible a wide application of the modelling techniques developed. The solution to population–resource problems usually requires that regional planners have at their disposal requisite information on predictable policy outcomes, in order to arrive at developmental decisions. This study of the central Dominican Republic may be considered a test case where problem-solving techniques have been developed and applied in order to achieve a greater understanding of the problems involved in watershed management in the tropics.

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### *Chapter 4*

# *Bioclimatology and Land Evaluation in Uganda*

*L. W. Hanna*

## Introduction

Land evaluation for agricultural development must be based on all the components of the physical environment but difficulties of data evaluation and classification mean that investigation and discussion must focus upon a few relevant criteria. In Uganda the high rate of evapotranspiration and the uncertainty of the rainfall combine to make water the most important single control over agriculture and explain the considerable interest in rainfall and in methods of conserving soil water (Russell, 1968). Most work has traditionally been concerned with the probability of receiving a critical rainfall total. However, more recent work on potential evapotranspiration has shown that a single rainfall value is inadequate to satisfy the wide range of atmospheric demands between the wetter lake shores of southern Uganda and the drier north. Moreover each crop makes individual demands of water both in total and seasonally. The scale of the agricultural enterprise is a relevant consideration as this determines the frequency with which the minimum water requirement must be received to avoid economic failure. Bioclimatology is concerned with the complex interactions between the climatic environment and plant life and can go a long way to remove the shortcomings of evaluations based upon rainfall alone. Water-balance studies related to agricultural production is an aspect of bioclimatology which has considerable importance to land evaluation. However, the characteristics of the water needs of a single crop are unique so that any map based upon water balance statistics cannot have direct application to agricultural land use or productivity. As yet insufficient relationships have

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Dr. Hanna is Lecturer in Geography in the University of Newcastle upon Tyne and was formerly Lecturer in Geography at Makerere University, Uganda.