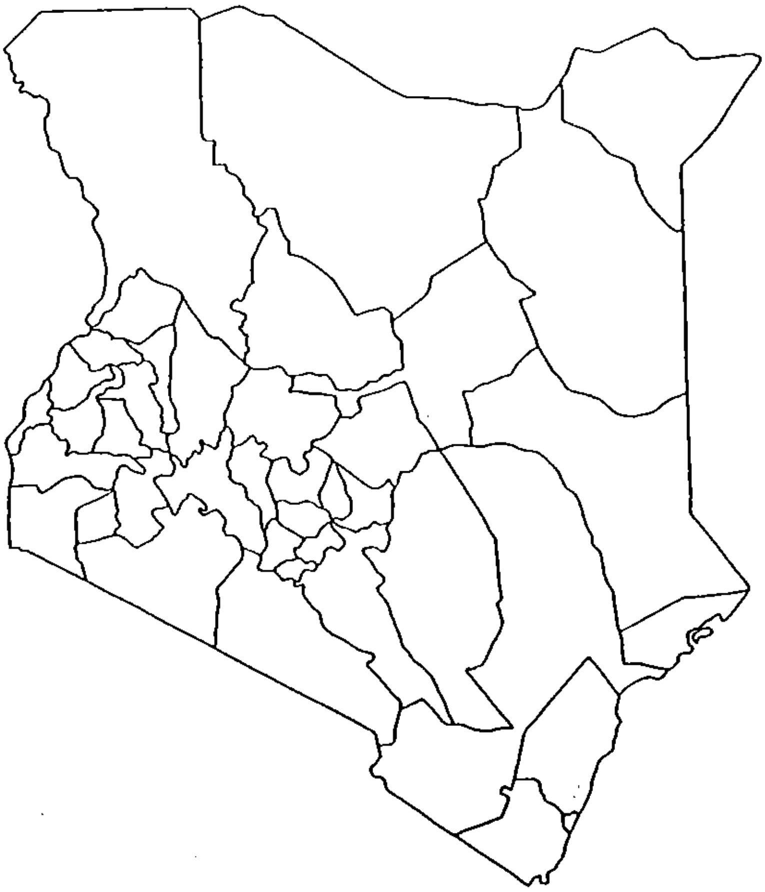
ASSESSMENT OF POPULATION SUPPORTING CAPACITY FOR DEVELOPMENT PLANNING IN KENYA

SOIL EROSION AND PRODUCTIVITY

Working Paper 4



Land and Water Development Division
Food and Agriculture Organization of the United Nations
and
rnational Institute for Applied Systems Analysis

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Final draft

ASSESSMENT OF POPULATION SUPPORTING CAPACITY FOR DEVELOPMENT PLANNING IN KENYA

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Any part of this soil erosion and productivity loss model and its parameters may be modified in the light of new knowledge and/or new objectives. The model is part of a larger district and national level planning tool and is expected to be expanded and refined with use.

CONTENTS

FIGURES

TABLES

TABLES (Continued)

TABLES (Continued)

REPORTS AND WORKING PAPERS

This work is recorded in three reports and nine working papers.

The three reports are:

1 Resources Data Base and Land Productivity

2 National Planning Scenarios and Models

3 Results and Policy Implications

The nine working papers are:

1 Climatic Resources

2 Land Resources

3 Land Use and Socio-economic Data

4 Soil Erosion and Productivity

5 Agro-climatic and Agro-edaphic Suitabilities for Barley, Oat, Cowpea, Green gram and Pigeonpea

6 Crop Productivity

7 Livestock Productivity

8 Fuelwood Productivity

9 Systems Documentation Guide to Computer Programmes

1 INTRODUCTION

The 'Assessment of Population Supporting Capacity for Development Planning in Kenya', is a programme concerned with the development and implementation of a national level methodology for the determination of land use potentials of land resources of individual districts for policy formulation and development planning. The programme has been carried out by FAO and IIASA in collaboration with the Government of Kenya (FAO 1984).

The work is described in three reports entitled: (i) Resources Data Base and Land Productivity, (ii) National Planning Scenarios and Models, and (iii) Results and Policy Implications. These three reports are supported by nine working papers which deal with technical details.

This working paper describes the model for the assessment of soil loss due to water erosion and its related impact on productivity of land. Effects of selected conservation measures for reducing soil loss together with costs implications of these measures are included.

This working paper is based on the work described in Mitchell (1986). For details of the derivation of equations and values, reference should be made to the above mentioned report. This working paper describes the soil erosion and productivity model, which quantifies implications of alternative land uses in terms of topsoil loss due to erosion and its impact on the productivity of land under different assumed soil conservation measures. The climatic and soil resources inventories on which the model operates are described in Working Papers 1 and 2 respectively.

2 METHODOLOGY

The methodology for the estimation of topsoil loss is essentially based a the Universal Soil Loss Equation (USLE): Wischmeier and Smith 1978). The topsoil loss is subsequently coverted into productivity loss with or without specific soil conservation measures. The methodology is schematically shown in Figure 2.1, and comprises of the following steps:

(i) Identification of land utilization types (LUTs), as defined for crop, livestock and fuelwood productivity models.

(ii) Determination of (USLE) factors for soil erosion: i.e. rainfall erosivity factor, soil erodibility factor, vegetation/crop cover factor, management factor and physical protection factor.

(iii) Application of USLE to quantify (LUT-specific) topsoil loss.

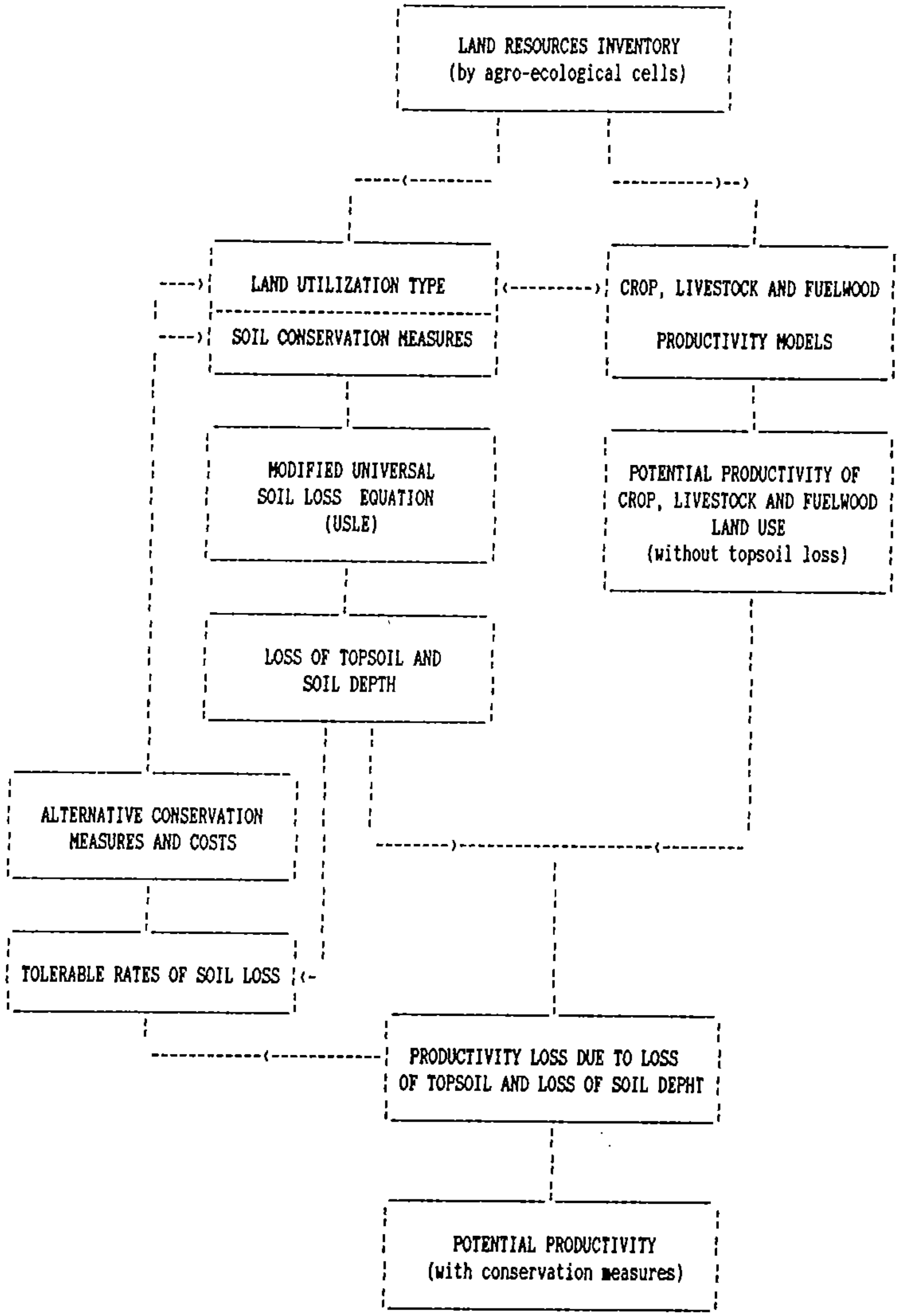

Figure 2.1 SCHEMATIC PRESENTATION OF THE SOIL EROSION AND PRODUCTIVITY MODEL

(iv) Establishing the relationships (equations) between loss of yield and loss of topsoil, and classifing soil units according to their susceptibility of yield loss due to loss of topsoil.

(v) Application of equations from (iv) to estimate productivity loss in relation to productivity potentials as quantified by the land use (crop, livestock, fuelwood) productivity models.

(vi) Derivation of productivity estimates, tolerable soil loss and costs for alternative conservation measures.

3 LAND RESOURCES

The land resources data base contains two layers of information on physical resources which allows the creation of unique ecological land units (agro-ecological cells) within which soil, landform and climatic conditions are quantified. This information, compiled at the national level by province and district, constitutes the inventory of the physical land resources.

The climatic resources part consist of three seperate thematic layers: the thermal zones layer, the length of growing period zones layer and pattern of number of length of growing period zones layer. The climatic resources inventory is described in Working Paper 1.

The soil resources layer includes information of soils, landform and geology/parent materials. The soil resources inventory is described in Working Paper 2.

Additional layers on land uses and administrative subdivisions have also been added. These layers contain inventories of cash crop zones, forest zones, parkland areas, irrigated areas, tse-tse infestation areas, and province and district boundaries.

The individual layers have been digitized. The digitized information derived from the individual layers has been coverted to a grid cell data base. The grid cell size is 100 ha.

Subsequent to digitizing, the soil map unit composition of each mapping unit and the associated edaphic conditions have been incorporated.

The make-up of the national land resources data base is schematically presented in Figure 3.1. The computerized land resources data base for Kenya records total extents of 35,475 agro-ecological cells. Each cell contains information on:

- Sequence number (NUM)
- Province (PRV)

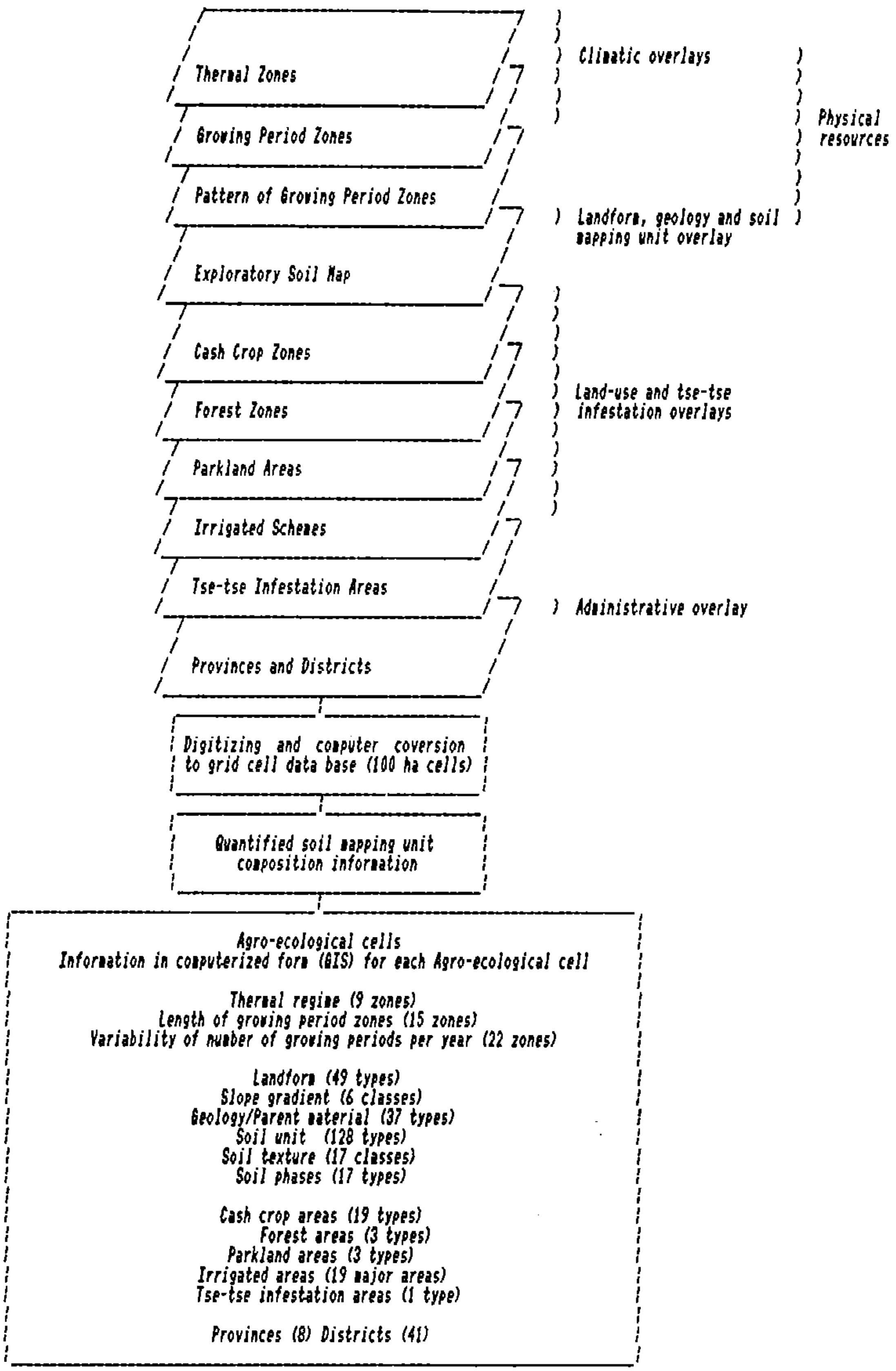

Figure 3.1 MAKE-UP OF LAND RESOURCES DATA BASE

- District (DIST)
- Thermal Zone (TZ)
- Length of Growing Period Zone (LGP)
- Pattern of Length of Growing Period Zone (PAT)
- Soil Mapping Unit (MPU)
- Landform (LNDFM)
- Geology/Parent Material (GEO)
- Soil Unit (SOIL)
- Soil Texture (TXT)
- Soil Phases (PHASES)
- Cash Crop Zone (CROP)
- Forest Zone (FOR)
- Irrigation Scheme (IRR)
- Tse-tse Infestation Areas (TSE)
- Parkland Area (PARK)
- Extent in hectares (EXTENT).

The land resources data base is available in the form of a grid based geographic information system (GIS). For details, reference should be made to Working Paper 9.

4 ESTIMATION OF SOIL LOSS

The Universal Soil Loss Equation (USLE) equates soil loss per unit area with the erosive power of rain, the amount and velocity of runoff water, the erodibility of the soil, and mitigating factors due to vegetation cover, cultivation methods and soil conservation. It takes the form of an equation where all of these factors are multiplied together:

$$A = R \times K \times LS \times C \times P \quad (4.1)$$

where:

A: Annual soil loss in t/ha

R: The rainfall erosion factor to account for the erosive power of rain, related to the amount and intensity of rainfall over the year. It is expressed in units described as erosion index units.

K: The soil erodibility factor to account for the soil loss rate in t/ha per erosion index unit for a given soil as measured on a unit plot which is defined as a plot 22.1 m long on a 9% slope under a continuous bare cultivated fallow. It ranges from less than 0.1 for the least erodible soils to approaching 1.0 in the worst possible case.

LS: A combined factor to account for the length and steepness of the slope. The longer the slope the greater the volume of runoff, the steeper the slope the greater its velocity. LS = 1.0 on a 9% slope, 22.1 m long.

C: A combined factor to account for the effects of vegetation cover and management techniques. These reduce the rate of soil loss, so in the worst case when none are applied, C = 1.0 while in the ideal case when there is no loss, C would be zero.

P: The physical protection factor to account for the effects of soil conservation measures. In this report conservation measures are defined as structures or vegetation barriers spaced at intervals on a slope, as distinct from continuous mulches or improved cultural techniques which come under the management techniques.

The USLE equation has been modified by separating the two elements of the cover and managment factor, C as follows:

C^*: The vegetation cover factor. This accounts only for the effects of the natural vegetation or crop canopy (including leaf litter and residues accumulating during the life of the crop).

M: The management factor. This accounts for tillage methods, the effects of previous crop residues, previous grass or bush fallows, and applied mulches.

The soil loss equation therefore becomes:

$$A = R \times K \times LS \times (C^* \times M) \times P. \qquad (4.2)$$

Equation 4.2 is used in the model to estimate soil losses, which in turn are related to productivity losses and conservation needs. The procedure (Figure 2.1) consist of the following main steps:

(i) Estimation of topsoil loss under specified vegetation/crop cover and management conditions for each land utilization type (LUT) as defined in the crop, livestock and fuelwood productivity models.

(ii) Estimation of productivity losses. The estimated soil losses are related to yield losses through a set of equations, taking into account the susceptibility of soils, and level of inputs.

(iii) Identification of conservation measures needed to reduce soil loss to an acceptable rate at quantified costs.

Each of the factors making up the soil loss equation 4.2 is quantified in turn, for a specified land use (LUT) or alternative land uses. Table 4.1 presents the attributes of land utilization types for crops. Attributes of land utilization types for pature (livestock) and fuelwood are given in Working Papers 7 and 8 respectively.

Table 4.1 **ATTRIBUTES OF LAND UTILIZATION TYPES**

Attribute	Low inputs	Intermediate inputs	High inputs
Produce and production	Rainfed cultivation of barley, maize, oat, pearl millet, dryland rice, wetland rice, sorghum, wheat, cowpea, green gram, groundnut, phaseolus bean, pigeonpea, soybean, cassava, sweet potato, white potato, banana, oil palm and sugarcane. Sole and multiple cropping of crops only in appropriate cropping patterns and rotations.		
Market orientation	Subsistence production.	Subsistence production plus commercial sale of surplus.	Commercial production.
Capital intensity	Low.	Intermediate with credit on accessible terms.	High.
Labour intensity	High, including uncosted family labour.	Medium, including uncosted family labour.	Low, family labour costed if used.
Power source	Manual labour with hand tools.	Manual labour with hand tools and/or animal traction with improved implements; some mechanization.	Complete mechanisation including harvesting.
Technology	Local cultivars. No fertilizer or chemical pest, disease and weed control. Fallow periods. Minimum conservation measures.	Improved cultivars as available. Appropriate Extention packages including some fertilizer application and some chemical pest, disease and weed control. Some fallow periods and some conservation measures.	High yielding cultivars including hybrids. Optimum fertilizer application. Chemical pest, disease and weed control. Full conservation measures.
Infrastructure requirement	Market accessibility not necessary. Inadequate advisory services.	Some market accessibility necessary with access to demonstration plots and services.	Market accessibility essential. High level of advisory services and application of research findings.
Land holding	Small, fragmented.	Small, sometimes fragmented.	Large, consolidated
Income level	Low.	Moderate.	High.

Note: No production involving irrigation and other techniques using additional water. No flood control measures.

4.1 Rainfall Erosivity (R)

4.1.1 Total erosivity of rain

Rainfall erosivity is an aggregate measure of the amounts and intensities of individual rain storms over the year. It is related to total rainfall (Moore 1978; Hudson 1981; Wenner 1981).

An overall correlation of total rainfall with length of growing period (LGP) has been used for this model. Table 4.2 shows how R is related to LGP, and gives the equations relating both to mean annual rainfall.

Table 4.2 **RELATIONSHIPS BETWEEN LENGTH OF GROWING PERIOD (LGP), MEAN ANNUAL RAINFALL (MAR) AND RAINFALL EROSIVITY (R)**

LGP[1] (days)	MAR[1] (mm)	R[2]
0	170	140
15	212	146
30	256	153
45	302	161
60	350	170
75	400	179
90	453	189
105	508	200
120	566	213
135	628	227
150	692	243
165	761	261
180	835	282
195	913	307
210	998	335
225	1,089	369
240	1,189	409
255	1,298	459
270	1,419	522
285	1,557	602
300	1,711	708
315	1,892	856
330	2,108	1,054
345	2,376	1,188
360	2,729	1,364
365	2,878	1,439

[1] $LGP = 400\ (1-1.0009^{(170-MAR)})$

[2] $R = 117.6\ (1.00105^{(MAR)})$ (for MAR <2000 mm)
$R = 0.5\ (MAR)$ (for MAR >2000 mm)

Figure 4.1 presents a generalized map of the rainfall erosivity factor (R).

4.1.2 Seasonal erosivity of rain

The following criteria are used to define the seasonal distribution of erosive rain during the growing period.

(i) A 'rainy season' for the purpose of this model is defined as being 95% of the corresponding length of growing period (i.e. rainy season ending before the end of the growing period).

(ii) In years with one length of growing period (monomodal rainfall pattern) all the erosive rain is assumed to fall during the rainy season or the adjusted growing period.

(iii) In years with two lengths of growing period (bimodal rainfall pattern) and more, erosive rain in the rainy seasons is assumed to be proportional to the component lengths of growing periods.

(iv) It is assumed that 50 per cent of the erosive rain falls during the first quarter of a rainy season. The remainder of the erosive rains are distributed evenly through the rest of the season.

4.2 Soil Erodibility (K)

The estimate of soil erodibility is based on the nomograph produced for the Universal Soil Loss Equation (Wischmeier and Smith, 1978), with some modification to account for the behaviour of three groups of soils (Nitisols, Vertisols and Chernozems), which appear to be more erodible than the nomograph indicates. The range of estimated erodibility values for Kenya soils has been divided into 7 classes, as follows:

Erodibility class	K value	
	mean	range
1	0.04	0 - <0.08
2	0.11	0.08 - <0.14
3	0.18	0.14 - <0.23
4	0.28	0.23 - <0.34
5	0.42	0.34 - <0.5
6	0.6	0.5 - <0.7
7	0.8	0.7 and over

Figure 4.1 GENERALIZED MAP OF THE RAINFALL EROSIVITY FACTOR (R)

Table 4.3 presents the soil erodibility class (K value) for each soil unit and for each soil texture listed as occurring in that unit. The mean K value of the soil erodibility class is used to calculate soil loss on any specified soil type. Figure 4.2 presents a generalized map of soil erodibility.

A cover of gravel or stones on the surface reduces erosion losses. The K value is reduced as follows to account for this protection:

(a) Stony, gravelly or bouldery phases: stone cover is assumed to be 25%, K value is multiplied by 0.7.

(b) Stone, gravel or boulder mantle phases: stone cover is assumed to be 50%, K value is multiplied by 0.4.

4.3 Slope-Length and Gradient (LS)

Two equations are used to give a figure combining the effects of the length and steepness of a slope; one for slopes up to 20% gradient, and one for steeper slopes (Arnoldus 1977). These are:

(a) for slopes up to 20%

$$LS = (L)^{0.5} \times (0.0138 + 0.00965S + 0.00138S^{2}) \qquad (4.3)$$

where:

L = slope length (m)
S = slope gradient (%)

(b) for slopes over 20%

$$LS = (L/22.2)^{0.6} \times (S/9)^{1.4}. \qquad (4.4)$$

Slope-gradients in Kenya are grouped into six classes by the Soil Survey of Kenya, and each mapping unit is assigned to one or a combination of up to three slope classes.

To each of the slope classes, associated slope classes have been assigned. These associated slope classes cover up to 10% of the land area. The inventoried slope classes and associated slope classes are presented in Table 4.4.

It is assumed for this model that a quarter of the land in each mapping unit is at the upper limit of the class to which it is assigned, a quarter is at the lower limit, and the two remaining quarters have intermediate slopes. Table 4.4 lists the slopes for each quarter of a mapping unit, for each slope class or combination of slope classes.

Table 4.3 SOIL ERODIBILITY CLASSIFICATION OF SOIL UNITS BY SOIL TEXTURE

Soil unit	Soil texture class: Sand	Loamy sand	Sandy loam	Loam	Clay loam	Sandy clay loam	Sandy clay	Clay	Silty clay	Silty clay loam	Silty loam	Silt	Sodic/saline phase (increase by one class)[1]
Acrisol - Humic	-	-	-	-	3	2	1	1	-	-	-	-	-
- Others	-	-	4	-	4	3	2	3	-	-	-	-	+1
Cambisol - Humic	-	-	-	-	3	2	1	1	-	-	-	-	-
- Others	-	-	4	5	4	3	2	3	4	5	-	-	+1
Chernozem	-	-	-	-	4	3	2	3	-	-	-	-	+1
Rendzina	-	-	-	-	-	-	4	5	-	-	-	-	-
Ferralsol - Humic;	-	-	-	-	-	-	1	1	-	-	-	-	-
- Nito-humic	-	-	-	-	-	-	1	1	-	-	-	-	-
- Others	-	-	4	-	-	3	2	2	-	-	-	-	-
Gleysol - Humic	-	-	-	-	-	-	2	2	-	-	-	-	-
- Mollic	-	-	-	-	-	-	2	2	-	-	-	-	-
- Others	-	-	-	-	-	-	2	3	-	-	-	-	+1
Phaeozem	-	-	-	-	3	3	1	2	-	4	-	-	+1
Lithosol	-	-	5	5	4	3	2	3	-	-	6	-	-
Fluvisol	-	-	4	5	4	4	2	3	-	4	6	-	+1
Kastanozem	-	-	-	-	4	-	-	-	-	-	-	-	-
Luvisol	-	-	3	3	3	3	2	3	-	-	-	-	+1
Greyzem	-	-	-	-	-	-	2	3	-	-	-	-	-
Nitisol - Ando-humic	-	-	-	-	-	-	-	4	-	-	-	-	-
- Others	-	-	-	-	-	-	3	3	-	-	-	-	-
Histosol	-	-	-	4	-	-	-	2	-	-	-	-	-
Arenosol	3	3	4	-	-	-	-	-	-	-	-	-	-
Regosol - Ando-calcaric	3	-	5	5	4	-	-	-	-	-	-	7	-
- Others	-	-	4	5	4	3	2	3	-	-	-	-	+1
Solonetz	-	-	5	-	4	4	3	4	-	-	6	-	*
Andosol	-	-	-	5	4	3	2	3	4	5	-	-	+1
Ranker	-	-	4	5	4	-	-	3	-	-	-	-	-
Vertisol	-	-	-	-	-	5	-	5	-	-	-	-	-
Planosol - Humic	-	-	-	-	3	-	-	2	-	-	-	-	-
- Others	-	5	5	5	4	4	3	4	-	5	-	-	+1
Xerosol/Yermosol	-	-	4	5	4	4	3	3	-	-	6	-	+1
Solonchak	-	-	5	6	5	4	3	4	5	-	7	-	*
Ironstone soil	-	-	4	-	4	3	-	3	-	-	-	-	-

[1] Saline /sodic conditions reduce permeability of the subsoil, consequently the erodibility factor K increases.

* Sodic/saline conditions are accounted for in these soils.

Figure 4.2 GENERALIZED MAP OF THE SOIL ERODIBILITY FACTOR (K)

The length of the slope is assumed to be limited to 150 m on slopes up to 16% and 100 m on slopes more than 16%. These slope-lengths represent the average distance that runoff would cover before reaching a drainage channel. Figure 4.3 presents a generalized map of the slope factor (LS).

Table 4.4 **ASSOCIATED SLOPE CLASSES**

Slope class Symbol	%	Associated slope classes		
A	0- 2	100% A		
AB	0- 5	100% AB		
B	2- 5	100% B		
BC	2- 8	90% BC	5% A	5% D
C	5- 8	90% C	5% AB	5% D
BCD	2-16	90% BCD	5% A	5% E
CD	5-16	90% CD	5% AB	5% E
D	8-16	90% D	5% BC	5% E
DE	8-30	90% DE	5% BC	5% F
E	16-30	90% E	5% BCD	5% F
EF	16-56	95% EF	5% BCD	
F	30-56	95% F	5% DE	

Table 4.5 **QUARTILES OF SLOPE CLASSES**

Slope range Class	%	Mean slopes of quartiles: Gentlest	Lower	Upper	Steepest
A	0- 2	0	1	1	2
AB	0- 5	0	2	4	5
B	2- 5	2	3	4	5
BC	2- 8	2	4	6	8
C	5- 8	5	6	7	8
BCD	2-16	2	6	11	16
CD	5-16	5	9	12	16
D	8-16	8	11	13	16
DE	8-30	8	16	22	30
E	16-30	16	21	25	30
EF	16-56*	16	30	42	56
F	30-56*	30	39	47	56

* 56% is taken to be the upper limit of slopes in the steepest slope class.

Figure 4.3 **GENERALIZED MAP OF THE SLOPE FACTOR (LS)**

4.4 Vegetation/Crop Cover (C*)

The total vegetation cover, and changes during the year, have to be related to the distribution of erosive rains to give an overall factor for protection by the vegetation canopy. In the case of annual crop production where different crops may be grown in rotation or alternated with fallows, an average protection factor is calculated for the full cycle.

Three types of land use are treated separately for estimating C*:

(a) Pastures and bushland
(b) Trees and shrubs (including forest and fuelwood plantations)
(c) Annual crops (including 2-season crops)
(d) Perennial crops.

4.4.1 Cover factors for pastures and bushland

The canopy cover of undisturbed vegetation, particularly the grass cover, is related to the rainfall. Grass cover fluctuates over the year according to the rainfall pattern. The main factors altering the relationship are grazing and clearing for cultivation.

(a) Grass cover:

Table 4.6 shows the seasonal maximum and minimum cover of grass in relation to grazing pressure and lengths of growing period. The minimum cover is the condition found at the start of the growing period, while the maximum is assumed to be reached 60 days later. The increase in canopy cover between those dates is assumed to be linear.

The table is based on figures for average present-day grazing pressure, whereby cover is assumed to be 20% more dense when land is ungrazed, and 50% less dense when land is overgrazed.

The cover factor (C*) for grassland with a specified percentage cover is presented in Table 4.7.

(b) Establishment of grass and bush cover after cultivation:

Table 4.8 shows the time taken for grass and bush cover to reach the same density as natural pastures on uncultivated land, at different levels of inputs.

It is assumed that pastures are sown or planted at the high and intermediate levels of inputs but not at the low level of inputs.

Table 4.6 SEASONAL GRASS COVER IN RELATION TO GRAZING BY LENGTH OF GROWING PERIOD (LGP)

LGP (days)	Grass cover (%) Ungrazed (a)	(b)	(c)	Average grazing (a)	(b)	(c)	Overgrazed (a)	(b)	(c)
0- 30	8	15	27	6	14	23	4	7	12
60-120	15	30	50	13	25	40	7	15	20
150-210	30	60	80	25	50	65	15	25	35
240-300	60	90	100	50	80	90	25	40	50
330-360	100	100	100	90	100	100	45	70	80

Notes: (a) = Minimum cover at the end of the dry periods
(b) = Maximum cover at the end of the shorter LGP
(c) = Maximum cover at the end of the longer LGP

Source: Dunne, Aubrey and Wahome (1981).

Table 4.7 COVER FACTOR (C*) FOR PASTURE

Vegetation cover (%)	Soil loss (in proportion to loss from bare soil)
0	1.0
10	0.33
20	0.20
30	0.15
40	0.10
50	0.07
60	0.042
70	0.024
80	0.013
90	0.008
100	0.003

4.4.2 Cover factor for trees and shrubs

The canopy cover of trees and shrubs, natural or planted, is related to the rainfall, and once established the cover remains relatively constant. The main factors altering the relationship are browsing and cutting trees for fuel or other uses, and clearing for cultivation.

Table 4.8 NUMBER OF YEARS REQUIRED TO REACH FULL PASTURE COVER BY LEVEL OF INPUTS CIRCUMSTANCES

Years after end of cultivation	Grass cover of pasture (percent of natural grassland cover for length of growing period given in Table 4.6)		
	Low inputs	Intermediate inputs	High inputs
1	40	90	90
2	70	100	100
3	100	100	100

The protective effect of a tree canopy depends on its height above the ground; tall trees have little effect as drops from their branches are almost as erosive as the rain. Low shrubs are very effective. The amount of litter, on the ground is also very important; a deep layer of litter reduces erosion to almost nil.

Table 4.9 shows the cover factor for trees and shrubs of differing heights. To estimate the cover factor (C*) for woodland, the density of tree and shrub cover can be estimated from vegetation maps, while the appropriate seasonal grass cover is found from the length of growing period. The respective cover factors for trees and shrubs (Table 4.9) and for grass (Table 4.7) are then multiplied together.

The cover factor of humid forest is largely due to a thick layer of litter protecting the soil surface (Table 4.10). This factor is a single measure combining the effects of trees, undergrowth and litter.

4.4.3 Cover factors for annual crops

The protective effect of an annual crop canopy varies from nil at planting to a maximum as the crop reaches maturity. The amount of erosion depends on the timing of the various stages of growth of a crop or combination of crops related to seasonal rainfall.

The following steps are used to calculate the cover factor for an annual crop or crop mixture:

(i) Set out the rainy seasons (in terms of length of growing period) on a calendar, with rainfall erosivity divided up into daily amounts according to the criteria in Section 4.1.2.

(ii) Set out the planting date, and the start and end of each stage of growth (crop stage) of each crop, on the calendar. Crop growth stages are given in Table 4.11, and they are:

Establishment (E): period	From sowing or planting to establishment of 10% cover
Early vegetative (Ev): period	End of establishment to start of bulking in root and tuber crops; end of establishment to start of stem elongation and yield formation in sugarcane; end of establishment to start of flowering in legumes, cotton and pineapple; end of establishment to start of head development in cereals and banana.
Late vegetative (Lv): period	Bulking period in root and tuber crops; yield formation period in sugarcane, legumes, cotton and pineapple; head development period and flowering in cereals and banana.
Maturation (M): period	Late yield formation and maturation in root and tuber crops, sugarcane, legumes and cotton; yield formation and maturation in cereals and banana.

Table 4.9 **COVER FACTOR (C*) DUE TO TREE AND SHRUB CANOPIES OF DIFFERENT HEIGHTS (SOIL LOSS AS PROPORTION TO LOSS FROM BARE GROUND)**

Ground cover by canopy (%)	Average fall height of drops			
	4 m	2 m	1 m	0.5 m
0	1.0	1.0	1.0	1.0
10	0.97	0.95	0.93	0.92
20	0.95	0.90	0.86	0.83
30	0.92	0.85	0.79	0.75
40	0.89	0.80	0.72	0.66
50	0.87	0.75	0.65	0.58
60	0.84	0.70	0.58	0.50
70	0.81	0.65	0.51	0.41
80	0.78	0.60	0.44	0.33
90	0.76	0.55	0.37	0.24
100	0.73	0.50	0.30	0.16

Source: Derived from Wischmeier and Smith (1978)

Table 4.10 COVER FACTOR (C*) FOR UNDISTURBED HUMID FOREST WITH LITTER LAYER AT LEAST 50 mm THICK

Area covered by canopy of trees and undergrowth (%)	Area covered by at least 50 mm of litter (%)	Soil loss (in proportion to loss from bare ground)
100	100	0.0001
75	90	0.001
50	75	0.003
20	40	0.009

Source: Adapted from Wischmeier and Smith (1978)

(iii) Find the maximum Leaf Area Index (LAI) of each crop. Leaf Area Index is used to estimate the percentage ground cover of the crop (Monteith 1969). Maximum LAI of single crops related to length of growing period and level of inputs are given in Table 4.12. When estimating maximum LAI for intercrops, it is suggested that the LAI of the first (main) crop is not reduced, but that of the second and subsequent crops is reduced by 25%.

(iv) Estimate crop cover at each crop stage of each crop.

(a) LAI at each crop state is as follows:

Crop Stage	LAI (percent of maximum)
E - Establishment	5
EV - Early vegetative	40
LV - Late vegetative	100
M - Maturation	80

(b) Crop cover is calculated from LAI by the equation:

$$C = 100\ (1-e^{(-KL)}) \qquad (4.5)$$

where:

C = Crop ground cover %
K = a constant based on geometry of crops: Table 4.13.
L = LAI

Table 4.11 CROP GROWTH STAGES AS PERCENTAGE OF THE TOTAL GROWTH CYCLE, FOR ANNUAL CROPS

Crop	Growth cycle (days)	Crop growth stage* and percentage of growth cycle			
		E	EV	LV	M
Barley	90 - 180	10	25	25	40
Maize (lowland),	70 - 130	16	20	20	44
Maize (highland)	130	15	19	19	47
	160	14	18	18	50
	190	13	16	16	55
	210	13	16	16	55
	250	12	15	15	58
	290	12	14	14	60
Oat	90 - 180	10	25	25	40
Pearl millet	60 - 100	16	20	20	44
Rice (dryland)	90 - 130	10	26	26	38
Rice (wetland)	80 - 140	10	26	26	38
Sorghum (lowland)	70 - 130	16	20	20	44
Sorghum (highland)	130	15	19	19	47
	160	14	18	18	50
	190	13	16	16	55
	210	13	16	16	55
	250	12	15	15	58
	290	12	14	14	60
Wheat	100 - 190	10	25	25	40
Cowpea	80 - 140	12	21	21	46
Green gram	60 - 100	12	21	21	46
Groundnut	80 - 140	11	26	26	37
Phaseolus bean	90 - 180	12	21	21	46
Pigeonpea	130 - 190	8	27	27	38
Soybean	80 - 140	8	27	27	38
Cassava	150 - 330	15	29	29	27
Sweet potato	115 - 155	15	29	29	27
White potato	90 - 170	15	29	29	27
Banana	300 - 365	10	25	25	40
Pineapple	330 - 365	15	35	35	15
Sugarcane	210 - 365	4	37	37	22
Cotton	160 - 180	12	34	34	22

E - establishment
EV - early vegetative
LV - late vegetative
M - maturation

Source : Adapted from Doorenbos and Kassam (1979).

Table 4.12 **MAXIMUM LEAF AREA INDEX (LAI) OF INDIVIDUAL CROPS BY CROP GROWTH CYCLE**

Crop	Length of growth cycle (days)	LAI* at high inputs level
Barley, wheat, oat	105	4.0
	145	4.5
	175	5.0
Maize, sorghum	80	2.5
(lowland)	100	3.0
	120	4.0
Maize (highland)	>120	4.0
Sorghum (highland)	>120	4.0
Pearl millet	70	3.0
	90	4.0
Rice (dryland)	100	3.5
	120	4.4
Rice (wetland)	90	4.0
	110	4.5
	130	5.0
Cowpea, groundnut,	90	3.0
Soybean	120	4.0
Green gram	70	2.5
	90	3.0
Phaseolus bean	105	3.5
	>135	4.0
Pigeonpea	>140	4.0
Cassava	>240	3.0
Sweet potato	120	3.5
	135	4.0
	150	4.5
White potato	100	3.0
	120	4.0
	150	5.0
Banana	>270	5.0
Sugarcane	>270	5.0
Cotton	170	3.0
Pineapple	>345	5.0

* LAI at Low input level is half, and at medium inputs level is three quarters, of LAI at high inputs level.

Source: FAO (1978); Kassam (1980).

Table 4.13 **K VALUES FOR LEAF CANOPIES OF INDIVIDUAL CROPS**

Crop	K
Cotton, cassava	1.0
Cowpea, groundnut, green gram, phaseolus bean, sweet potato white potato	0.85
Maize, sugarcane	0.70
Barley, oat, rice, wheat	0.70
Pearl millet, sorghum	0.60
Soybean, pigeonpea, pineapple	0.45
Banana	0.90

Source: Derived from Monteith (1969).

(v) Estimate the cover of crop residues remaining after harvest. A relationship between crop residues and maximum LAI is given in Table 4.14.

(vi) For crop mixtures, record the crop cover for each crop stage on the calendar.

(vii) Estimate the combined crop cover of all crops in the mixture at each period on the calendar for which they are different using the equation:

$$T_i = T_{i-1} + \frac{(100-T_{i-1})}{100} C_i \qquad (4.6)$$

where:

T_i - the total percentage cover of i crops
C_i - the percentage cover of the "ith" crop in the crop mixture.

(viii) Estimate the cover factor for the combined annual crops for each period on the calendar Table 4.15.

(ix) Multiply the cover factor for each period by the daily rain erosivity and the number of days in each period. This gives the proportion of erosive rain that actually reaches the ground and is able to cause erosion. If the amounts for each period are totalled and divided by the annual erosivity R, the resultant fraction represents the annual cover factor C* for all the crops grown on the land.

The procedure described above can cover any combination of intercrops and sequential annual crops. To compute C*, the required variables for a given farming system are:

- Length of growing period (LGP)
- LGP-Pattern (monomodal, bimodal or trimodal)
- Planting dates and length of growth cycle for each crop
- Percentage of the growth cycle of each crop occupied by the different growth stages (Table 4.11)
- Maximum LAI for each crop (Table 4.12)
- Constant K for each crop, relating LAI to ground cover percent (Table 4.13)
- Amount of crop residues, related to LAI (Table 4.14).

Table 4.14 **AMOUNT OF CROP RESIDUES AFTER HARVEST, IN RELATION TO MAXIMUM LEAF AREA INDEX OF THE CROP**

Crop	Type of residues	Equivalent LAI (% of maximum)
Barley, oat, rice, wheat	Stubble: standing crop removed	60
Cowpea, green gram, groundnut, p. bean, soybean, sweet potato	Wilted, fallen stover (some may be removed for fodder)	60
Maize, pearl millet sorghum, potato, cassava	Standing or fallen left in the field	80
Cotton, pigeonpea	Standing crops	80
Sugarcane	Cut cane-tops and leaves	95
Pineapple, banana	Standing crop	95
Oil palm	Standing crop	100

Table 4.15 **COVER FACTOR (C^*) FOR CROPS**

Vegetation cover (%)	Soil loss (in proportion to loss from bare soil)	
	Annual crops	Low perennial crops
0	1.0	1.0
10	1.0	0.33
20	1.0	0.20
30	1.0	0.15
40	0.86	0.10
50	0.72	0.07
60	0.58	0.042
70	0.44	0.024
80	0.30	0.013
90	0.16	0.008
100	0.02	0.003

Source: Derived from Othieno (1972); Elwell and Stocking (1976); Barber and Thomas (1981), Colvin and Laflen (1981); Elwell and Stocking (1982)

4.4.4 Reduction of crop cover due to soil factors and intermediate lengths of growing periods

Soil limitations and dry conditions reduce the growth of crops and hence the ground cover, to varying extents.

Soil factors may reduce productivity by reducing overall growth while the harvest index remains the same (for example soil fertility). In this case the leaf area index (LAI) would drop in proportion to the loss in yield, or they may reduce yield but not vegetative growth (for example nutrient imbalance, or shallow soils lacking moisture storage at the end of the rains), in which LAI may not be reduced significantly.

The soil factors used in the model represent a combination of both types of factors, so it is assumed for this model that the reduction of LAI due to soil limitations will be half the reduction in productivity. Thus if productivity is halved, LAI will be reduced by 25%.

Intermediate lengths of growing periods are growing periods in which rainfall does not exceed potential evapotranspiration (PET) at any time. The average rainfall is assumed to be 0.75 PET. This will create stress in vegetatively growing crops, and reduce the maximum cover. It is assumed that the reduction in cover would be as follows:

Crop stage E: No reduction (water requirement is below 0.75 PET at these stages)

Crop stages EV, LV and M: LAI is reduced by 25%.

4.4.5 Cover factors for perennial crops

Perennial crops are assumed to have a 'constant' cover once established.

Tall perennial crops can be classified according to the height of the canopy, in the same way as trees and shrubs (Table 4.9).

Low-growing bushy perennials (tea, pyrethrum) are classed as having the same protective effect as pasture (Table 4.15).

Possible rates of establishment and final maximum cover of perennial crops are presented in Table 4.16.

Table 4.16 **POSSIBLE MAXIMUM COVER DENSITY OF PERENNIAL CROPS, AND NUMBER OF YEARS TO REACH IT**

Crop	Low and Intermediate levels of inputs level		High level of inputs	
	Final cover density percent	Time to reach final density years	Final cover density percent	Time to reach final density years
Tea	100	4- 5	100	3
Coffee	60	4- 5	80	3
Pyrethrum	60	3- 4	80	2
Oil palm	40	8-10	60	6
Banana	60	2- 3	80	1
Sisal				
T1	60	3- 4	70	2
T2, T3	60	5- 6	70	4

4.5 Management (M)

The management factor defines the effects of cultivation methods, mulches, manures and previous crops or pastures on soil erosion. Three subfactors are evaluated and multiplied together to estimate the management factor:

M1: Soil loss is estimated for flat cultivation (i.e. without ridging) with subsequent cultivation producing a fine seedbed, in cropland not following a grass or bush fallow. The effect of flat cultivation, including incorporation of previous crop residues, is evaluated through Tables 4.17 and 4.18.

M2: The value of flat cultivation is modified to account for improved soil protection using other cultivation techniques. Additional protection due to cultivation techniques other than flat cultivation is given in Table 4.19.

M3: The value is further modified to account for effects of previous grass or bush fallow and of farmyard manure and surface mulch, adjusted to account for more rapid decomposition in higher-temperature zones as given in Table 4.20.

Management effects vary to some extent during the growing period, and the factors listed above are related to the crop stages of the dominant crop in the case of intercropped system. In a case where two successive crops are grown in a single continuous growing period, the second crop is regarded as a new seperate crop for estimating the duration of mulch effects.

4.6 Physical Protection (P)

Physical soil conservation measures include both excavated works such as cut-off ditches or terraces and thus the use of vegetation in the form of trash lines or grass strips. They differ from cultural techniques in that they are applied at intervals on a slope, and they often involve taking a part of the land out of use for annual crops.

Physical conservation measures considered in the model are: small farms (manual or ox cultivation) - grass strips, trash lines, contour stone terraces, cut-off ditches (graded to outfall), converse terraces ('fanya juu', on the contour), step-terraces (for cash crops tea and coffee), and bench terraces (for cash crops tea and coffee); large farms (>50 ha, mechanically cultivated) - grass strips and narrow-based terraces (V-shaped terraces). These various measures act in different ways to reduce soil loss, and their effectiveness and costs are described in Section 6.

Table 4.17 SOIL LOSS RATIOS TO BARE FALLOW FOR FLAT CULTIVATION, IN RELATION TO PREVIOUS CROP: SUBFACTOR M1

Previous crop	Amouunt of residues [1]	Ratio of soil loss to loss from bare fallow at crop stage: [2]	
		F	E,EV,LV,M,R
Bare fallow[3]	nil	0.9	1.0
Cropland, no residues left	a	0.9	1.0
	b,c	0.8	0.9
	d	0.7	0.8
Cropland, dug in residues	a	0.8	0.9
	b	0.7	0.8
	c	0.6	0.8
	d	0.5	0.7

[1] Refer to Table 4.18.

[2] Crop stages refer to the dominant crop, in case of crop mixtures.

F - rough cultivation
E - sowing to establishment
EV - early vegetative
LV - late vegetative
M - maturation
R - residue or stubble

[3] If land is cultivated after a bush or grass fallowe, use this factor. The effect of fallow is given in Table 4.20.

4.6.1 Systems designed to divert runoff water: channel terraces and bench terraces

Cut-off drains, narrow-based terraces and bench terraces divert runoff water across the slope, discharging it into channels away from the cultivated land. The effect is to reduce the length of slope between structures, and therefore soil erosion (Hammer 1981; Wenner 1981; Foster and Highfill 1983).

(a) **Cut-off drains:** A cut-off drain is used to protect farmland from uncultivated slopes above. It is assumed to divert all runoff water, therefore slopes on farmland are defined as starting from the cut-off drain.

The protective effect of a cut-off drain, in the absence of other conservation measure, is assumed in this model to reduce the slope length by half, i.e. to 75 m on slopes up to 16% and to 50 m on slopes over 16%.

Table 4.18 **AMOUNT OF CROP RESIDUES REMAINING AT THE END OF THE DRY PERIOD IN RELATION TO THERMAL REGIME, LENGTH OF GROWING PERIOD AND LEVEL OF INPUTS**

Crop	Thermal Zone	Level of inputs	Approximate amount of residues[1] at beginning of crop growing period following harvest					
			Length of growing period (days)					
			60-89	90-119	120-149	150-179	180-209	>209
Maize	1 - 3	Low	a	a	b	b	b	b
Pearl millet	(>20°C)	Int.	a	b	b	c	c	d
Sorghum		High	a	b	c	d	d	d
Barley	4 - 5	Low	a	a	b	b	b	b
Oat	(15-20°C)	Int.	a	b	c	c	d	d
Wheat		High	b	c	d	d	d	d
Rice	6 - 7	Low	a	b	b	c	c	c
	(10-15°C)	Int.	b	c	c	d	d	d
		High	b	c	d	d	d	d
Cassava	1 - 3	Low	a	a	a	b	b	b
Sweet potato	(>20°C)	Int.	a	a	b	b	b	c
White potato		High	a	b	b	c	c	c
P. bean	4 - 5	Low	a	a	b	b	b	b
Soybean	(15-20°C)	Int.	a	b	b	c	c	c
Groundnut		High	a	b	c	c	c	d
Cowpea	6 - 7	Low	a	a	b	b	b	b
Green gram	(10-15°C)	Int.	b	b	c	c	c	c
Pigeonpea		High	b	b	c	d	d	d

[1] a: <1 t/ha c: 4-8 t/ha
b: 1-4 t/ha d: >8 t/ha

Residue values refer to land assessed as S1 (very suitable). Residue values are 25%, 50% and 75% lower respectively for land assessed as S2 (suitable) or S3 (moderately suitable) or S4 (marginally suitable).

Source: FAO (1978).

Table 4.19 SOIL PROTECTION FACTORS FOR CULTIVATION TECHNIQUES OTHER THAN FLAT CULTIVATION: SUBFACTOR M2

Cultivation Technique	Management subfactor M2					
	F[1]	E	EV	LV	M	R
Nil cultivation with planting holes	1.0	1.0	1.0	1.0	1.0	1.0
Row-planting and weeding:						
- not on the contour	1.0	1.0	1.0	1.0	1.0	1.0
- on the contour	1.0	1.0	0.9	0.9	0.9	0.9
Ridge cultivation on the contour:						
- A slopes (0-2%)	1.0	0.6	0.6	0.6	0.6	0.6
- B slopes (2-5%)	1.0	0.5	0.5	0.5	0.5	0.5
- C slopes (5-8%)	1.0	0.5	0.5	0.5	0.5	0.5
- D slopes (8-16%)	1.0	0.7	0.7	0.7	0.7	0.7
- E slopes (16-30%)	1.0	0.9	0.9	0.9	0.9	0.9
- F slopes (>30%)	1.0	1.0	1.0	1.0	1.0	1.0
Tied ridging on the contour:						
- A slopes (0-2%)	1.0	0.3	0.3	0.3	0.3	0.3
- B slopes (2-5%)	1.0	0.25	0.25	0.25	0.25	0.25
- C slopes (5-8%)	1.0	0.25	0.25	0.25	0.25	0.25
- D slopes (8-16%)	1.0	0.4	0.4	0.4	0.4	0.4
- E slopes (16-30%)	1.0	0.6	0.6	0.6	0.6	0.6
- F slopes (>30%)	1.0	1.0	1.0	1.0	1.0	1.0
Stubble-mulch cultivation:						
- Zero residues	-	1.0	1.0	1.0	1.0	1.0
- Low yield	-	0.4	0.5	0.6	0.7	0.7
- Moderate yield	-	0.25	0.3	0.35	0.4	0.4
- High yield	-	0.08	0.10	0.12	0.13	0.13

[1] see footnote in Table 4.17.

(b) **Narrow based terraces:** The maximum slope on which narrow-based terraces are recommended is 20%. Their protective effect is partly due to reduction in slope-length and partly due to silt deposition on the slope next to the terrace channel. Two P subfactors are used to calculate the protective effect: slope-length reduction factor (Table 4.21), and silt deposition factor (Table 4.22).

Table 4.20 EFFECT OF PREVIOUS GRASS OR BUSH FALLOW, FROM FARMYARD MANURE, AND SURFACE MULCHES ON SOIL LOSS RATIOS FROM CULTIVATED LAND[1,2]: SUBFACTOR M3

Treatment	Management subfactor M3					
	F	E	EV	LV	M	R
First season after grass/bush fallow:[3]						
- very sparse, < 30% cover	0.6	0.8	0.8	0.9	1.0	1.0
- sparse, 30-60% cover	0.35	0.5	0.5	0.55	0.6	0.7
- Moderate, 60-90 % cover	0.30	0.45	0.45	0.50	0.55	0.65
- Dense, > 90% cover	0.25	0.40	0.40	0.45	0.50	0.60
Second season after grass/bush fallow:[4]						
- very sparse, < 30% cover	1.0	1.0	1.0	1.0	1.0	1.0
- sparse, 30-60% cover	0.8	0.9	0.9	0.95	1.0	1.0
- Moderate, 60-90 % cover	0.75	0.85	0.85	0.9	0.95	1.0
- Dense, > 90% cover	0.7	0.8	0.8	0.85	0.9	0.95
Farmyard manure spread and ploughed in:[4]						
- < 5 t/ha	1.0	1.0	1.0	1.0	1.0	1.0
- 5-10 t/ha	0.8	0.9	0.9	0.95	1.0	1.0
- > 10 t/ha	0.75	0.85	0.85	0.90	0.95	1.0
Surface mulch, spread or in crop rows:						
- 1 t/ha 45% cover	-	0.35	0.35	0.4	0.4	0.45
- 2 t/ha 65% cover	-	0.2	0.2	0.25	0.25	0.3
- 4 t/ha 80% cover	-	0.1	0.1	0.12	0.12	0.15
- 6 t/ha 90% cover	-	0.07	0.07	0.09	0.09	0.12

[1] The figures assume a fallow of at least 3 years duration, for shorter fallows, multiply by 1.5 for two years fallow and 2.0 for 1 year fallow (If result >1.0, use 1.0).

[2] The values shown apply to cool conditions (Thermal zones 6-8), for thermal zones 4-5 and 1-3 multiplication factors of 1.2 and 1.4 respectively to be applied (If result >1.0, use 1.0).

[3] Percent cover is the cover at the end of the dry season; the cover at the end of fallows shorter than 3 years is reduced by the amount shown in Table 4.8.

[4] Farmyard manure is assumed to consist of cattle manure with little added straw or litter.

(c) **Bench terraces and step terraces:** Bench terraces are rarely constructed except on steep land intended for coffee planting. Step terraces (narrow terraces each with a single row of coffee) are recommended on slopes over 30%, and bench terraces on slopes between 12 and 30%. The effectiveness of terraces is due to both the reduction in slope-length depending on terrace interval and the reduction in slope-gradient on the terraces themselves.

In the model, bench terraces are not considered at the low level of inputs. At the intermediate level of inputs, medium standard terraces without provision for water disposal are considered (P = 0.15). At the high level of inputs, high standard terraces with provision for water disposal are considered (P = 0.04).

Table 4.21 **REDUCTION OF SLOPE-LENGTH FACTOR DUE TO TERRACING, IN RELATION TO LENGTH OF UNPROTECTED SLOPES**

Terrace interval (m)	Slope length factor (L) reduction from:	
	150 m (Up to 16% slope)	100 m (Over 16% slope)
3- 4	0.15	0.2
5- 7	0.2	0.25
8- 11	0.25	0.3
12- 16	0.3	0.4
17- 21	0.35	0.45
22- 27	0.4	0.5
28- 33	0.45	0.55
34- 42	0.5	0.6
43- 49	0.55	0.7
50- 56	0.6	0.7
57- 63	0.6	0.8
64- 72	0.7	0.8
73- 84	0.7	0.9
85- 90	0.8	0.9
90-100	0.8	1.0

Table 4.22 **P SUBFACTOR FOR DEPOSITION ON NARROW-BASE TERRACES IN RELATION TO TERRACE INTERVAL AND CHANNEL GRADIENT**

Terrace interval	Channel gradient (%)				
	Level	0.1-0.3	0.4-0.7	0.7-0.8	> 0.8
< 33	0.5	0.6	0.7	0.8	1.0
33-42	0.6	0.7	0.8	0.9	1.0
43-54	0.7	0.8	0.8	0.9	1.0
55-68	0.8	0.8	0.9	0.9	1.0
69-90	0.9	0.9	0.9	1.0	1.0
> 90	1.0	1.0	1.0	1.0	1.0

4.6.2 Systems designed for trapping silt and runoff: converse or 'fanya juu' terraces

Converse terraces are constructed by throwing soil upslope from a contour ditch. Runnoff water and silt are trapped above the bank, which gradually builds up to form bench terraces. Their protective effect is due to reduction in both the length and gradient of slopes (Thomas, Barber and Moore 1980; Barber, Thomas and Moore 1981; Wenner 1981; Thomas 1983).

Three P subfactors are multiplied together to give a P factor for converse terraces:

- Slope-gradient reduction factor (Table 4.23)
- Slope-length reduction factor (Table 4.24)
- Establishment of grass on terrace banks (Table 4.25)

4.6.3 Systems designed for trapping silt but no run-off: grass strips, trash lines and contour stone terraces

The purpose of these systems is to slow runoff, which increases infiltration next to the structure and causes some of the silt to be deposited (Mitchell 1965; Othieno 1965; Moore, Thomas and Barber 1979; Barber and Thomas 1981; Thomas 1983; Watson 1984). The result, as with converse terraces, is that a terrace is gradually built up, but the effective slope-length is only partly reduced on the amount of runoff absorbed.

(a) **Grass strips**: The effect with grass strips is approximately equivalent to the slope-length reduction factor for converse terraces (Table 4.24). The effectiveness of grass strips depends on how well the

Table 4.23 **PROTECTION SUBFACTOR (Ps)[1] FOR SLOPE-GRADIENT REDUCTION BY CONVERSE TERRACES (BASED ON AN OPTIMUM VERTICAL INTERVAL OF 1.5 m)**

Original slope gradient (%)	Horizontal interval between terraces (m)				
	5	10	15	25	50
2	0.04	0.07	0.11	0.18	0.36
5	0.06	0.12	0.17	0.29	0.56
8	0.07	0.15	0.22	0.37	0.73
11	0.09	0.17	0.26	0.43	0.87
16	0.11	0.21	0.32	0.52	1.0
20	0.12	0.24	0.36	0.61	1.0
30	0.18	0.37	0.55	0.92	1.0

[1] The protection factor (Ps) is modified to account for soil permeability, and risk of damage by run-off and possible collapse of banks, by multiplying by: 3 x ($K^{0.32}$), where: K = soil erodibility.

Table 4.24 **PROTECTION SUBFACTOR (Pl) FOR SLOPE-LENGTH REDUCTION BY CONVERSE TERRACES**

Terrace interval	Soil erodibility (K) class						
	1	2	3	4	5	6	7
Slopes <16%							
50	0.63	0.72	0.81	0.93	1.0	1.0	1.0
25	0.46	0.55	0.63	0.73	0.85	0.94	0.99
15	0.37	0.45	0.53	0.62	0.72	0.81	0.85
10	0.31	0.39	0.46	0.55	0.64	0.72	0.76
5	0.23	0.31	0.37	0.45	0.53	0.59	0.63
Slopes >16%							
50	0.72	0.83	0.94	1.0	1.0	1.0	1.0
25	0.49	0.59	0.69	0.81	0.95	1.0	1.0
15	0.37	0.46	0.55	0.66	0.79	0.89	0.95
10	0.30	0.39	0.47	0.57	0.68	0.78	0.83
5	0.21	0.29	0.35	0.44	0.53	0.61	0.65

grass is established, which in turn depends on length of growing period. The suggested modification to the slope-length reduction factor is the same as for converse terraces (Table 4.25).

(b) **Trash-lines**: The effect with trash-lines is approximately equivalent to the slope-length reduction factor for converse terraces (Table 4.24). The effectiveness of trash-lines depends on the availability of materials. This is related to the net biomass production of the crop. A relationship between the minimum possible spacing and the amount of crop residues is given in Table 4.26. The relationship between available residues, climate and level of inputs is given in Table 4.16 with the following adjustments: a = 0 t/ha, b = 2 t/ha, c = 6 t/ha, d = 10 t/ha.

Table 4.25 **PROTECTION SUBFACTOR DUE TO ESTABLISHMENT OF GRASS ON TERRACE BANKS**[1]

Length of growing period	Grass cover	P subfactor
< 150 days	Poor	2
150 - 240 days	Average	1
> 240 days	Good	0.5

[1] Assuming good management. (Poor management, particularly uncontrolled grazing, would reduce the grass cover).

Table 4.26 **SPACING OF TRASH-LINES RELATED TO AVAILABILITY OF DRY CROP RESIDUES**

Crop residues (t/ha)	Minimum possible interval between effective trash-lines (m)
1	50
2	25
3	17
4	12.5
5	10
6	8
8	6
10	5

(c) **Contour stone terraces:** The effect with trash-lines is approximately equivalent to the slope-length reduction factor for converse terraces (Table 4.24). The effectiveness of stone terraces depends on the availability of materials which in turn depends on the stoniness of the surface. Table 4.27 relates the percentage stone cover on the surface to the minimum possible terrace interval.

Table 4.27 **POSSIBLE INTERVALS BETWEEN STONE TERRACES RELATED TO STONE COVER**[1]

Stone cover (%)	Weight of stones (t/ha)	Possible interval between stone terraces (m)
2.5	50	40
5	100	20
10	200	10
20	400	5

[1] Stony phases are assumed to have a 10% cover of stones suitable for stone terraces, stone mantle phase 20% cover.

5 SOIL EROSION AND LOSS OF PRODUCTIVITY

The effect of soil erosion can be measured in different ways according to the kind of damage suffered. In the model (Figure 2.1), the estimate is based on short-term losses in crop production due to erosion of fertile topsoil, and long-term losses in land productivity due to truncation of the soil profile and consequent reduction of available water. No account is taken at this stage in the model development of possible damage to lowlands by flooding and silt deposition, or of the possible benefit from the deposition of fertile silt on alluvial plains, or increase in workability constraints due to changes in terrain characteristics.

In the model, permissible slopes for various land uses under different levels of inputs circumstances have been defined as model variables, and these are given in Table 5.1. The critical slope values in the slope-land use association screen define the upper slope limits to cultivation, and they may be modified as appropriate.

Table 5.1 **SLOPE-CULTIVATION ASSOCIATION SCREEN**

Land utilization type	Level of inputs Low	Intermediate	High
Dryland crops without soil conservation measures	<30%	<30%	<16%
Dryland crops with soil conservation measures	<30%	<30%	<30%
Wetland crops without soil conservation measures	< 5%	< 5%	<2%
Wetland crops with soil conservation measures[1]	<30%	<30%	<30%
Coffee, tea, fuelwood and pasture with and without soil conservation measures	<45%	<45%	<45%

[1] For wetland crops, terracing is required.

Further, the model takes into account the loss in crop production by soil erosion through:

(a) the removal of topsoil which, in many soils, is the source of most or all the nutrient fertility; and

(b) reducing the overall depth of the soil profile so that eventually the soil water holding capacity and foothold capacity are reduced to a point where it limits yields.

An acceptable rate of soil erosion is considered to be one that over a specified number of years (e.g. 25, 50 or 100):

(a) does not result in a crop yield reduction of more than a specified amount due to loss of topsoil; and

(b) does not result in more than a specified proportion of land being downgraded to a lower class of agricultural suitability due to soil depth reduction.

These two criteria are not interdependent, so that acceptable rate of soil loss is taken as the lower of the two alternatives. The model therefore provides a framework for assessing tolerable soil loss, based on its likely impact on crop yields and the future availability of cultivable land.

The soil erosion and productivity model (Figure 2.1) is linked to crop, livestock and fuelwood productivity models which provide the assessments of land suitabilities and the associated yield potentials for the estimation of tolerable soil loss.

5.1 Effect of Topsoil Loss on Productivity

Soils differ in their susceptibility to loss of productivity as the topsoil is eroded. The differences are related to the depth of the topsoil and the amount of nutrient fertility or presence of unfavourable conditions in the subsoil.

Loss of productivity due to topsoil loss can be largely compensated by the use of manure and fertilizer, and low rates of soil erosion are compensated to some extent by the formation of new topsoil. The rate of topsoil formation can vary from < 0.25 mm/year in dry and cold environments to > 1.5 mm/year in humid and warm environments (Hammer 1981; Hudson 1981). Topsoil formation at the rate of 1 mm/year is equivalent to an annual addition of 12 t/ha. Therefore, the rate of topsoil formation has been considered as a factor in the model in assessing loss of productivity and tolerable soil losses. Regeneration capacities of soils used in the model in calculating net loss of topsoil are given in Table 5.2 by moisture and thermal regimes.

<u>Table 5.2</u> **REGENERATION CAPACITY OF TOPSOIL (mm/year) BY LENGTH OF GROWING PERIOD (LGP) AND THERMAL ZONE**

LGP (days)	Thermal Zone T1	T2	T3	T4	T5	T6	T7	T8	T9
< 75	0.5	0.5	0.5	0.5	0.5	0.25	0.25	0.25	0.25
75 - 119	1.0	1.0	1.0	0.5	0.5	0.25	0.25	0.25	0.25
180 - 269	1.5	1.5	1.5	0.75	0.75	0.5	0.5	0.5	0.5
> 270	2.0	2.0	2.0	1.0	1.0	0.5	0.5	0.5	0.5

Derived from Hammer (1981).

Based on experimental evidence (Stallings 1957; Barr 1957; Lal 1976a, 1976b, 1976c; Higgins and Kassam 1981) and analytical data from Kenya Soil Survey (KSS 1975, 1976, 1982b), soil units of the Exploratory Soil Map of Kenya have been classified according to their susceptibility to productivity loss with loss of topsoil, and on the presence of other unfavourable subsoil conditions (Table 5.3). These rankings of susceptibility of the soils are related to actual yield losses, by inputs level, through a set of linear equations given in Table 5.4. The reduced impact of topsoil loss under intermediate and high levels of inputs is due to the compensating effect of fertilizers at their normal rates of use. It is assumed that the benefit of fertilizers is less on the more susceptible soils because of their more unfavourable subsoil conditions.

<u>Table 5.3</u> **RANKING OF SOILS (KENYA SOIL SURVEY) ACCORDING TO THEIR SUSCEPTIBILITY TO PRODUCTIVITY LOSS PER UNIT OF TOPSOIL**

Most susceptible	Intermediate susceptible	Least susceptible
Acrisols, except Humic Acrisols	Arenosols	Chernozems
Ferralic cambisols	Cambisols, except Ferralic Cambisols	Fluvisols
Ferralsols, except humic Acrisols	Gleysols	Histosols
Ironstone soils	Greyzems	Humic Andosols
Lithosols	Humic Acrisols	Mollic Andosols
Planosols	Humic Ferralsols	Vertisols
Rendzinas	Kastanozems	
Solonchaks	Luvisols	
Solonetz	Nitisols	
	Phaeozems	
	Regosols	
	Vitric Andosols	
	Xerosols	
	Yermosols	

The tolerable loss rate, for a given soil unit and specified amount and time scale of yield reduction, is calculated in the model as follows:

$$TL = (Ra/Rm \times 100\ B \times Dt) + 3T \qquad (5.1)$$

where:

TL = tolerable loss rate (t ha^{-1} $year^{-1}$)
Ra = acceptable yield reduction (%)
Rm = yield reduction (%) at the given inputs level when the effective topsoil is all lost
B = bulk density of the soil (g/cm^3)
Dt = depth of effective topsoil (cm)
T = time (years) over which yield reduction is acceptable.

Table 5.4 **RELATIONSHIPS BETWEEN TOPSOIL LOSS AND YIELD LOSS**

Soil susceptibility ranking	Levels of inputs	Equation
Least susceptible	Low	Y = 1.0 X
	Intermediate	Y = 0.6 X
	High	Y = 0.2 X
Intermediate susceptible	Low	Y = 2.0 X
	Intermediate	Y = 1.2 X
	High	Y = 0.4 X
Most susceptible	Low	Y = 7.0 X
	Intermediate	Y = 5.0 X
	High	Y = 3.0 X

Y = productivity loss in percent; X = topsoil loss in cms.

5.2 Effect of Soil Depth Reduction on Productivity

The rate of soil formation by rock weathering is extremely slow, up to 0.025 mm/year on volcanic rocks in humid areas, and < 0.01 mm/year on basement complex rocks in semi-arid areas (Dunne, Dietrich and Brunego 1978). At the highest rate quoted by Dunne *et al.* (1978), it would take 4,000 years to produce 10 cm of soil. Therefore, the rate at which the soil profile is deepened by rock weathering has not been considered as a factor in the model in assessing tolerable soil losses.

The estimation of the effect of soil depth reduction is based on the assumtion that there is no significant loss of productivity until the soil becomes so shallow that shortage of moisture becomes a limiting factor. The critical depth varies according to crop and the climate. Once this critical depth is reached, productivity loss is linear until the soil becomes to shallow to produce any crop at all (Wiggins and Palma 1980). The critical points can be equated with land suitability class limits as follows (where depth is the limiting factor):

VS/S: Soil water becomes limiting and there is at least 20% decrease in yield potential

S/MS: Soil water becomes limiting and there is at least 40% decrease in yield potential

MS/mS: Soil water becomes limiting and there is at least 60% decrease in yield potential

mS/N: Soil water becomes limiting and there is at least 80% decrease in yield potential.

The land suitability classes VS (very suitable), S (suitable), MS (moderately suitable), mS (marginally suitability) and N (not suitable) correspond to yield levels of >80%, 60-80%, 40-60%, 20-40% and <20% of maximum attainable yield respectively.

If erosion takes place uniformly on soils of varying depth, the end result will be that some soils that had been marginally deep enough will become non-productive while others will become marginal. If the range of soil depths is known, the tolerable amount of soil loss can be gauged in terms of the amount of land that can be permitted to be lost to production.

In order to calculate tolerable soil losses, soil depth reduction is measured in terms of the proportion of the soils in a specified area that have become shallower than a given depth, as a result of erosion. The soils of the mapping units of the Exploratory Soil Map of Kenya (KSS 1982a) are assigned to 5 depth classes: shallow, < 50 cm; moderately deep, 50-80 cm; deep, 80-120 cm; very deep, 120-180 cm; extremely deep, >180 cm.

The rate of soil loss is related to the proportion of land whose soil has become shallower than a specified depth, by the following equations:

(a) Proportion (P, percent) of land downgraded to at least the next depth class:

$$P = (SL \times T) / (B \times Dr) \qquad (5.2)$$

where:

SL = soil loss (t ha^{-1} $year^{-1}$)
T = time (years)
B = bulk density of the soil (g/cm^3)
Dr = depth range of the soil class (cm).

(b) Proportion (P, percent) of land downgraded by more than one depth class:

$$P = \frac{[(SL \times T)/100B]}{Dr} - D2 \times 100 \qquad (5.3)$$

where:

D2 = difference (cm) between the lower limit of the depth class and the upper limit of the shallower class to which the land is downgraded
Dr = depth range of the soil class (cm).

Table 5.5 shows the proportions of land downgraded from given depth classes to shallower classes as a result of soil erosion at different rates over a 100 years period. The values in Table 5.5 are based on equations 5.2 and 5.3, and assume that soil depths are evenly distributed over the range in each depth class.

Table 5.5 THE PROPORTION OF LAND DOWNGRADED FROM GIVEN DEPTH CLASSES TO SHALLOWER DEPTH CLASSES OR TO BEDROCK AS A RESULT OF SOIL EROSION AT DIFFERENT RATES OVER A 100 YEAR PERIOD

Soil depth class and change (cm)	Amount of land downgraded (% of class) at erosion rates (t/ha) of:							
	5	10	25	50	75	100	200	400
From shallow (0-50)								
to bedrock (0)	8	17	42	83	100			
From moderately deep (50-80)								
to shallow (0-50)	14	28	70	100				
to bedrock (0)	0	0	0	0	42	100		
From deep (80-120)								
to moderately deep (50-80)	10	21	52	100				
to shallow (0-50)	0	0	0	29	81	100		
to bedrock (0)				0	0	8	100	
From very deep (120-180)								
to deep (80-120)	7	14	35	70	100			
to moderately deep (50-80)	0	0	0	3	38	72	100	
to shallow (0-50)				0	0	22	100	
to bedrock (0)						0	78	100
From extremely deep (200-400)								
to very deep (120-180)	2	4	9	19	28	38	76	100
to deep (80-120)	0	0	0	0	1	11	48	100
to moderately deep (50-80)					0	0	30	100
to shallow (0-50)						0	17	92
to bedrock							0	70

If a tolerable soil loss was set to allow 10% of each depth class to be downgraded by one class over 100 year period, this would give the following soil loss rates for each depth class (assuming 25 cm is the minimum soil depth that would allow crop production):

Shallow (to 25 cm) - 3 t ha^{-1} $year^{-1}$
Moderately deep - 3.6
Deep - 4.8
Verydeep - 7.2
Extremely deep - 26.8.

5.3 Assessment of Tolerable Soil Loss on a Combined Basis of Topsoil Loss and Soil Depth Reduction

Criteria for estimating soil loss tolerance are set according to the amount of yield loss that can be tolerated, or the proportion of the land that can be permitted to become shallower than a specified depth, over a specified time. The two basis for soil loss estimation do not interact, so when used in combination the tolerable soil loss would be the lower of the estimates.

An example of the soil losses that would give either a 50% yield reduction or soil depth reduction resulting in downgrading of 10% of each depth class, over a period of 100 years, is given in Table 5.6.

Table 5.6 **TOLERABLE RATES OF SOIL LOSS (t ha^{-1} $year^{-1}$) TO GIVE NOT MORE THAN 10% LOSS OF LAND FROM A GIVEN DEPTH CLASS AND NOT MORE THAN 50% CROP YIELD REDUCTION AT LOW INPUT LEVEL OVER A 100-YEAR PERIOD**

Soil depth class	Susceptibility to yield loss of topsoil		
	Low	Intermediate	High
Shallow[1]	3.0	3.0	3.0
Moderately deep	3.6	3.6	3.6
Deep	4.8	4.8	4.8
Very deep	7.2	7.2	7.2
Extremely deep	12.0	26.4	26.4

[1] Assuming a minimum depth of 25 cm for crop production.

6 SOIL CONSERVATION MEASURES

Three kinds of benifits can be obtained from soil conservation on cultivated land:

(a) Long-term reduction or halting of decline in agricultural production or availability of good quality land.

(b) Immediate or gradual increase in agricultural production.

(c) Non-agricultural benefits such as improved dry season flow of rivers, reduced flooding and siltation of reservoirs, and reduced damage to infrastructure and farm land on lower slopes.

The soil erosion and productivity model essentially quantifies the long-term benefits (i.e. reducing or preventing further losses of agricultural land and decline in crop yields) of seven soil conservation measures for alternative uses of land. It is envisaged that the model would be extended in the future to include an estimation of other agricultural and non-agricultural benefits implied in (b) and (c) above.

Seven types of conservation measures are considered in the model: cut-off drains, narrow-based terraces, bench terraces, converse terraces ('fanya juu' terraces), grass strips, trash-lines, and stone terraces. Of these, narrow-based terraces and grass strips are suitable for large farms, while all measures except narrow-based terraces are suitable for small farms. Bench terraces can be used on large farms, but the costs of making them wide enough for mechanical cultivation is high. Also, as seen in Section 4, narrow-based terraces are applicable to slopes $< 20\%$, whereas effectiveness of grass strips is reduced in low rainfall areas (LGP <150 days) because of poor establishment. Also, trash-lines are subject to availability of crop residue whereas stone terraces are subject to availability of stones, and are feasible only on stony soils.

In the application of the soil erosion and productivity model (Figure 2.1), potential erosion losses for each desired land use (crop, livestock, fuelwood) is evaluated first on the assumption that no specific soil conservation measures are applied, i.e. protection factor $P = 1$. The results are compared with what is considered as acceptable rates of soil loss under the three levels of inputs circumstances, and then the required amount of conservation and associated costs are estimated.

6.1 Estimation of Conservation Need

The need for soil conservation is estimated from the protection factor (P) required to reduce soil erosion from its average rate on unprotected land to the tolerable rate estimated in Section 4. The average rate of erosion covers both the cultivated and the uncultivated parts of the crop and fallow period cycle, but the soil conservation measures described are only applied and maintained in the cultivated part of the cycle. If unacceptable rates of erosion are also occuring during the uncultivated part of the cycle, then additional protection will be needed.

The following example shows how conservation need is estimated in the model, for the cultivated part of the crop and fallow period cycle.

Year		Annual soil loss (t/ha)	Total soil loss (t/ha)
1- 4	(Rest period)	4	16
5	(Crop, 1st year)	12	12
6	(Crop, 2nd year)	18	18
7-10	(Crop, 3rd - 6th year)	25	100

Total soil loss over 10 years			146
Tolerable rate of soil loss over 10 years		8	80

Soil loss reduction needed is 66 t/ha (i.e. 146-80). The total soil loss over 6 years of the crop cycle is 130 t/ha, which has to be reduced by 66 t/ ha to 64 t/ha. The P factor needed to achieve this is 64/139 = 0.49.

The protective effect of conservation measures varies according to natural conditions - soil, topography, climate - and the intensity of the measure, e.g. the interval between terraces.

The equations to calculate the required spacing for a given measure, when the relevant natural conditions and the required protection - P factor - are known, are given in Mitchell (1986). These equations form the basis of cost calculations in the model for the seven types of conservation measures listed above.

These conservation measures deal with cultivated land, and in the model their benefit is assumed to last only while the land is under cultivation. If excessive erosion is taking place during the uncultivated part of a crop-fallow period cycle, the most effective way to reduce it is by improving the grass cover. The first requirement for this is to reduce or eliminate the grazing pressure of livestock. Tables 4.7 and 4.8 (Section 4) show the percent grass cover at different times of the year, and assumed rates of regeneration of grass cover after cultivation, in relation to climate and grazing intensity. These can be used to estimate the effect on soil erosion of reducing the intensity of grazing.

Other possible causes of excessive erosion on uncultivated land are poor established grass due to low rainfall, and unfavourable soil conditions. These have not been explicitly incorporated in the model at this stage in its development, but possible measures to overcome them are: pasture improvement with fertilizers; planting of improved pasture species or broadcasting seed; use of lines of cut bushes to slow runoff to protect germinating grass seeds; use of small earth banks to trap water to encourage germination of broadcast seed (Critchly 1984).

6.2 Costs of Conservation Measures

The costs of conservation measures are given in terms of man-days of labour, and the proportion of land taken out of agricultural production by the measures. Where fertilizer is used, for example in establishing grass strips, the amount of fertilizer is specified. It is assumed that all materials used are locally available and therefore not explicitly costed.

Table 6.1 presents a generalized comparison of the characteristics, effectiveness and costs of the seven types of conservation measures considered in the model.

The appropriate conservation measure for a given set of circumstances is normally the cheapest that will achieve the required measure of protection. The costs presented in Table 6.1 are based on man-days of work for manual labour. These include initial costs and maintenance costs. Initial costs are mainly based on the horizontal interval between measures, whereas annual maintenance costs are derived as fixed percentage of the initial costs. In order to compare costs directly, the annual maintenance costs over the cultivated part of the 10-year crop and fallow cycle are coverted to net present value using an interest rate of 10%.

Most conservation measures involve taking some land out of production. They vary according to the type of measure, and whether the plants used to protect the terrace banks and other structures have any production value.

Table 6.1 ECONOMIC ASPECTS OF SOIL CONSERVATION MEASURES

Type of measure and physical protection factor (P)	Slope (%)	Horizontal interval (m)	Height of risers (m)	Initial cost: Construction (man-day/ha)	Initial cost: Grass planting (man-day/ha)	Initial cost: Fertilizer (kg/ha)**	Annual maintenance cost (man-day/ha)	Proportion of land taken out of agriculture (%)
Cut-off drains	<16	-	-	27	-	-	3	-
P = 0.25-0.75 *	>16	-	-	40	-	-	4	-
Narrow-based	5	40	1.0	50	17	5	5	5
terraces	8	20	1.0	100	36	10	10	10
P = 0.1-0.4 *	16	10	1.6	200	51	15	20	15
	32	5	1.6	400	102	30	40	30
Bench terraces	12	8	1	1000	44	12	104	6
	12	16	2	2000	44	12	204	6
P = 0.05-0.15 *	16	6	1	900	58	16	96	8
	16	12	2	1800	58	16	186	8
	24	4	1	750	88	24	84	10
	24	8	2	1500	88	24	159	10
	32	2.8	1	630	125	36	76	13
	32	5.5	2	1270	125	36	140	13
	56	1.4	1	400	250	72	65	22
	56	2.8	2	800	250	72	105	22

* Guideline ranges for physical protection factor (P) under good management only.
** 50% sulphate of ammonia and 50% triple superphosphate.

Source: Derived from Mitchell (1986); Vlaanderen (1989).

Table 6.1 (Continued)

Type of measure and physical protection factor (P)	Slope (%)	Horizontal interval (m)	Height of risers (m)	Initial cost: Construction (man-day/ha)	Initial cost: Grass planting (man-day/ha)	Initial cost: Fertilizer (kg/ha)**	Annual maintenance cost (man-day/ha)	Proportion of land taken out of agriculture (%)
Converse terraces	5	20	1.0	100	17	5	18	5
	8	16	1.3	125	22	6	22	6
P = 0.05-0.15 *	16	8	1.3	250	44	12	44	13
	32	5	1.3	400	72	20	72	20
Grass strips	5	40	-	-	9	2	1	2.5
	8	20	-	-	18	6	3	5
P = 0.35-0.75 *	16	10	-	-	35	10	5	10
	32	5	-	-	70	20	10	20
Trash-lines	5	40	-	1	-	-	1	2.5
	8	20	-	2	-	-	2	5
P = 0.35-0.75 *	16	10	-	3	-	-	3	10
	32	5	-	5	-	-	5	20
Stone terraces	5	40	0.4	50	-	-	5	1.5
	8	20	0.4	71	-	-	7	3
P = 0.35-0.75 *	16	10	0.4	125	-	-	13	6
	32	5	0.4	235	-	-	24	12

* Guideline ranges for physical protection factor (P) under good management only.

** 50% sulphate of ammonia and 50% triple superphosphate.

Source: Derived from Mitchell (1986); Vlaanderen (1989).

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