Guidelines for Watershed Management

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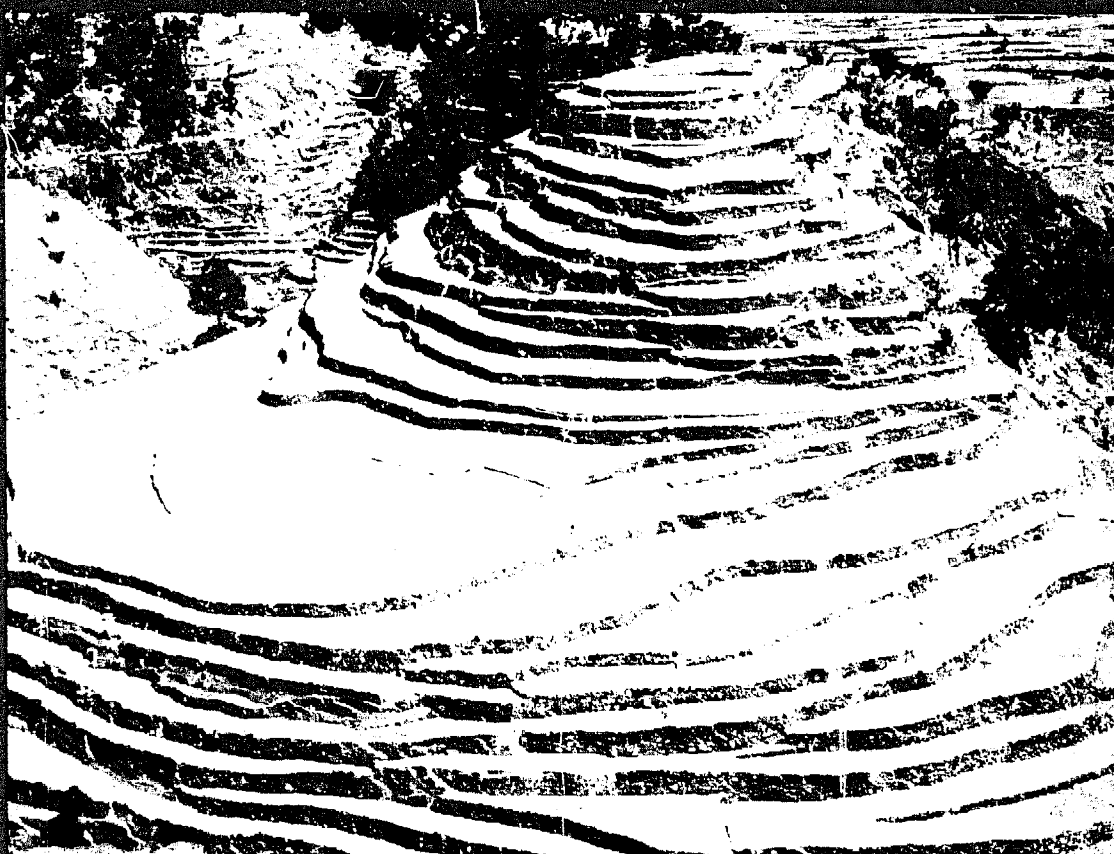

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FAO CONSERVATION GUIDE 1

guidelines
for
watershed management

forest conservation and wildlife branch
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ABSTRACT

This "Conservation Guide" is one of a series of publications which illustrate conservation techniques, examples of land rehabilitation and watershed management principles, primarily for mountain lands, forests, eroded areas and other lands not normally used for intensive agriculture. The papers are based on case studies from all regions but are mainly oriented to provide practical examples of interest to developing countries. The topics in the volume presented here include: erosion evaluations, watershed management principles, erosion control methods, land classification, land use planning, slope rehabilitation by terracing, remote sensing for watershed management, the cost/benefit relations of conservation, landslide problems, environmental impact evaluations and water quality measurements.

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FOREWORD

Water appears to have been the critical factor in many of the areas of the world which have experienced famine during the last few years. A large proportion of the droughts and floods which have occurred in recent times, in almost all the regions of the world, could have been avoided if the knowledge available to mankind had been adequately disseminated and properly utilized. Unfortunately, Homo sapiens seems unable to learn from the lessons which history has to offer. This, despite the fact that there are devastated lands all over the world which mutely testify to the catastrophes which are bound to occur if land is mismanaged and misused in critical ecological areas.

The importance of water is, of course, obvious in the more arid regions of the world. But it should be emphasized that even in those humid areas of the tropics that appear to be blessed with an abundance of water, there have been long and frequent periods in which there has been an insufficiency of water. This, precisely because mankind has not always appreciated or taken into account the inter-actions of the various factors of the ecosystem.

In many countries, the clearing of the uplands for agriculture has depleted the vegetation to such an extent that the flow of the rivers which they supply becomes "flashy" during the rainy seasons and a trickle during the dry seasons. The results are floods in the wet and droughts in the dry periods. The consequences of this are often a failure of the crops, followed by famine, malnutrition and the attendant human suffering.

The usual simplistic solution, that is often suggested and unfortunately put into effect in cases like these, is the construction of dams to control river flows and to protect more valuable downstream lands. However, in many instances the effectiveness of these dams is short-lived because they become affected by silt which is washed down from the depleted uplands. Therefore, the few benefits which accrue from the dams are short-term and provide no lasting improvement to the total system. More important, and more regrettable, the temporary security offered by the structures may lead to a precarious over-development in the lower reaches of rivers.

In order to be lastingly effective, soil and water resource development must be preceded by comprehensive land-use planning. In the formulation of these plans, both the attributes of the land and water resource, and the socio-economic factors which affect the development of the human beings in the area in general, and land-use practices in particular, should be taken into account. Moreover, there should be provision for perpetual operational support. Without adequate social control of the use of the world's land and water resources, their technological over-development can lead in the long run to regional or national under-development. Furthermore, there must be an awareness of the total soil and water resource system, both upstream and downstream, and of the inter-related benefits that can be obtained by the wise application of modern technology.

The material presented in the four volumes of this series attempts to relay some of the experience of scientists and technologists who have had a broad association with some of the problems of the soil and water conservation aspects of watershed management in the developing countries. A special effort has been made to obtain a cross-section of authors from around the world with this experience. It is our hope that planners and practitioners in the developing world will find the series of practical value.

K. F. S. King

K. F. S. King
Assistant Director-General
and
Head of the Forestry Department
Food & Agriculture Organisation of the UN

PREFACE

This "FAO Conservation Guide" is one of a series of readings which provide some practical examples and case studies of conservation and land protection from various regions of the world. The emphasis of the series is on protection forests, rangelands, steep terrain and other areas where the returns from land use are marginal, where degradation is a problem or where resource protection is (or should be) a major objective. The main emphasis is on techniques which may be useful for developing countries.

The "FAO Conservation Guides" are:

Number 1: "Watershed Management Guidelines". This collection of papers reviews the concepts of watershed management and conservation and illustrates practical methods for: erosion and degradation surveys; erosion prediction; gully correction; some remote sensing techniques for watershed management; forest road protection against erosion; environmental impact evaluations; terracing; steep slope restoration; and protection against landslides.

Number 2: "Hydrological Techniques for Upstream Conservation". This group of papers reviews some aspects of forest hydrology and other essentially "upstream" questions of hydrology related to conservation work. There are examples of: field runoff estimation; torrent control; infiltration estimation; snow surveys for water in the mountains; evaluation of mountain land degradation; recycling of wastewater in forests; stream water quality evaluations; transpiration; and surveys of sedimentation in reservoirs.

Number 3: "Conservation of Arid and Semi-Arid Zones". This selected group of papers reviews desertization and presents examples of shelterbelt establishment, dune afforestation, erosion evaluation, terracing for slope afforestation, restoration of rangelands, rainfall harvesting and other techniques.

Number 4: "Special Readings in Conservation Techniques". These papers are an assortment of readings which are more specialized or research oriented. The topics covered are: guidelines for controlled fires for forest conservation; concepts of snow management in high mountains; a case study of mulches for soil restoration; and research techniques for soil temperature estimation.

I.

LAND CLASSIFICATION FOR WATERSHED MANAGEMENT[1/]

by

K. F. S. King[2/]
FAO

1. INTRODUCTION

Classification is a device designed to achieve the orderly and systematic arrangement of ideas and phenomena. Gilmour (3) has emphasized that the primary function of classification is to construct classes about which inductive generalizations may be made. The classes so constructed must be related to a particular purpose. The purpose of the type of classification which is the subject of this paper is the delineation of areas which are inherently capable of producing plant and animal crops of a broadly similar nature, without deterioration of the soil. Put in another way, the objective of this paper is to indicate how land may be classified according to its inherent capability to produce crops.

At the outset it is necessary to distinguish between land classification and land-use planning. These are different processes. They demand different types of expertise; their competent execution often requires a knowledge of widely varying disciplines. In the process of land classification the scientist or technologist surveys, inventories and evaluates the physico-chemical and meteorological characteristics of the land areas which he wishes to classify. After these initial stages, the land classifier should have at his disposal data that are adequate enough to allow him to place similar types of land into particular classes. The placing of an area of land into any one class will depend upon a combination of the broad factors which influence productivity viz climate, topographic relief and soil characteristics. The object of land classification is to distinguish what exists, and to enable the planner to appreciate the inherent difference in quality of the land at his disposal. The land classification lays bare to the economists, the politicians and the decision-makers the potentiality of the land, and the physical options which are available to them, at least in so far as land is concerned. And it does this in an easily understandable manner. The land-use planner draws upon the land classification and complements and supplements it. To the physical land classification which has categorized the differences between different areas of land, the land-use planner adds his knowledge of the economic, legal, social and institutional factors which affect land-use, and which are germane to decision-making. From this synthesis a land-use plan may be born.

2. TYPES OF LAND CLASSIFICATIONS

An examination and analysis of published work on land classification systems which have been evolved for land utilization reveal five generic types. These may be classified as empirical, socio-economic, plant indicator, qualitative and physical. Olson (12) has distinguished nine types, but all fit generically into the five types of classification described below.

1/ This paper draws heavily on King, K. F. S. (9)

2/ Kenneth King is Assistant Director-General of FAO, and Head of its Forestry Department.

2.1 Empirical Classifications

In the initial stages of most disciplines, before knowledge has been systematized, and before principles have been formulated, man has to be guided by experience. He has to infer a general law from the observation of particular instances. The approach is empirical and the thought process is inductive. Some classifiers have observed existing types of land-use, appraised their success or failure, and drawn conclusions about the inherent capability of the land.

The assumption, that present use is indicative of capability, is not always valid. It is indeed possible that there are areas in which the inhabitants have achieved such a degree of technological skill and experience that the present use of the land is its best use. But these must be very exceptional. Often, land-use has been adapted by social pressures and bears little relation to the land's inherent capacity.

Nevertheless, surveys of present land-use have an important part to play in land-use planning. Classifications so formulated, however, should be called Current Land-Use Classifications and should be clearly distinguished from Land Classifications. The purpose of a Current Land-Use Classification is to indicate how the land is at present being utilized. The operation is essentially one of stock-taking and, as such, its importance should not be minimized. It becomes suspect, however, when its claims are exaggerated, when it is suggested that land productivity may always be inferred from present land-use, and that land capability classes may be formulated from these data alone.

2.2 Socio-economic Classifications

Some workers have evolved methods of expressing the potential productivity of land, by taking account of such factors as (i) the nature of the society which utilizes the land, (ii) the financial returns which are the result of such use, (iii) the size and condition of farm buildings, (iv) tax delinquency, (v) school and farm location, (vi) land ownership, (vii) quantity and quality of available labour, (viii) the financial ability of the operator, and (ix) the operator's preferences and abilities.

Socio-economic factors are dynamic and are based only in part on the characteristics of the land. They are concerned with an additional dimension: time. In addition, economic rent is influenced, *inter alia*, by population concentration, industrialization, and the availability of alternative occupations. Economic classifications are, therefore, not inextricably tied to the land. Economists have a place in the planning of land-use, but little in the classification of land. The term land classification should be confined to those classifications that restrict their data-base to the physical aspects of land areas.

2.3 Plant Indicator Methods

From earliest times observers have associated certain plants or types of vegetation with definite soil and growth conditions, although there has been some controversy as to whether individual species are a better guide to land capability than the vegetation as a whole.

The relationship between natural vegetation and the inherent productivity of the land can be determined only after very careful ecological study. The vegetation is a reflection of the interplay of soil climate, biotic factors and the vegetation itself, and a satisfactory cause effect relationship can only be determined when the physiological requirements of the individual species and the vegetation are ascertained. It is a most complex problem, and our knowledge is so imperfect that the system cannot be universally applied. Moreover, as Jacks (6) has said, vegetation is less durable than soil, and, in many areas, the natural vegetation has already been destroyed.

2.4 The Quantitative Approach

In the early stages of the development of any branch of science, the assessment of the interplay of cause and effect is often qualitative. At a later stage, when sufficient information is available, the approach becomes quantitative. Perhaps the best known of the attempts to provide a quantitative basis for the measurement of land capability are Storie's (16) index rating, Kendall's (7) productivity, ranking, energy and money-value co-efficients, the Tennessee Valley Authority's unit area method, and Stamp's (14) and (15) concept of the Potential Production Unit.

The purist may claim that these classifications are not strictly quantitative because they do not measure and correlate the numerous variables that are known to influence land productivity. They merely depart from the more orthodox descriptive and qualitative methods by providing figures to delineate and distinguish classes of land. There is another, more fundamental, criticism. Many of these attempts at quantification are based on systems in which such factors as the angle of slope, the depth of soil, soil texture, fertility and climate are rated or weighed. Weighting is a subjective process, and in many cases the assignment of rates appeared to have been made quite arbitrarily or to have been influenced by the philosophy of the classifier.

2.5 Physical Classifications

The physical factors which influence plant productivity and which should therefore be taken into account when constructing land capability classifications are reasonably well known. The significance of the physical and chemical nature of the soil, the limitations and attributes of various topographical features, and effects of climate are well documented. The problem is really one of synthesising these various factors in order to forge a workable tool.

Stamp (13) evolved a land classification for Great Britain in which he used topographical, soil and water relations in order to distinguish between three major land categories: good, medium and poor. Ableiter (1) suggested that as the "soil type" represented a combination of characteristics which together occupy a particular kind of landscape in which the factors of soil genesis are essentially uniform this should be used as the basis for classification: Weeks (19) et al. introduced the concept of "land character types". A land character type embraces several soil types and is essentially a large-scale inventory of the physical conditions significant to land-use: and Hills and Boissonneau (4) took into account the "land-form", which they defined in terms of the relief of the land and the geological materials which constitute this relief. The relief feature most generally considered was slope pattern, but another factor was the fabric of geological materials, i.e. the size and shape of individual rock particles or masses, and the manner in which these particles are aggregated. They claimed that the landform concept was universal in application because areas of similar slope pattern and fabric are classified as the same landform irrespective of their regional location, and because they are relatively stable features, changes being largely restricted to stages in the geological cycle. But the landform classification is not an all-sufficing system. It is merely the stable reference base upon which changes in soil may be measured and interpreted in terms of land-use capabilities.

Olson (12) has asserted that in Australia, parts of Africa, and in some other places, the "land systems approach" has been widely used in land classification. This technique generally identifies areas with reasonably similar and recurring characteristics of climate, vegetation, geology, soils, land-use and topography. The areas are mapped at different scales, and generally extensive chemical, morphological and physical analyses are made. The claims made for the "land systems approach" are similar to those made for the "landform" method. The defects are also similar.

The examples given above are not exhaustive. They are merely illustrative of the differences in approach which may perhaps have been caused by the difficulty of integrating the numerous variables which influence land capability.

3. A METHODOLOGY FOR LAND CLASSIFICATION

The relative importance of topographical relief, climate and soil is difficult to assess. Therefore, most land classifications have been, to some degree, subjective. A more objective assessment of land capability may be achieved if the problem is approached differently, and no attempt is made to synthesise the factors, but instead a process of elimination is employed which will lead to a broad classification of potential use. This approach is based on the concept of limiting factors and is essentially an adaptation of the principle of Liebig's Law of the Minimum. The physical factors which ultimately decide to what use land may be put are generally those which exercise a limiting influence, are absent or are in critical short-supply. It is therefore important when classifying land to subject the land, so to speak, to a series of tests, the results of which would lead to the isolation of those areas which display a similarity of limitation and ought therefore to be placed in the same classes. Residual land, land with few or no limitations, would of course be the best land.

The first question which should be asked is whether there are areas in the region to be classified which are climatically unsuitable for plant production: whether the climate is a limiting factor. It is tempting to try to evolve comprehensive formulae which express the relationships of the various climatic influences, but such formulae are of little use unless they are tested empirically, and they are frequently applicable only to the regions for which they were evolved. Those formulae which are extant are either of merely local application, or are too general as they relate to the broad regions of the world. The land classifier must consult the available climatic records and ensure that they cover as wide a range in time and space as possible; mean data are of little significance: what are more important are the distribution and the extremes of the climatic factors: particular attention must be paid to temperature, precipitation, evapo-transpiration, and the influence of altitudinal changes on these factors. A map, more detailed and comprehensive than the ordinary climatic maps, must then be prepared. From this map the areas which are unproductive because of adverse climatic factors may be ascertained, so classified, and excluded from the subsequent investigation.

The next step is to consider topographical relief. Altitude, aspect, and the degree of slope are the important relief features, but the influence of altitude and aspect is reflected in the climate, which has already been investigated; consequently, the angle of slope as it is significant to erosion, is the only topographical feature which must be treated separately at this stage.

Strahler (17) has suggested a method of quantitatively estimating the amount of erosion which would occur on slopes of known angles and in areas of known rainfall intensity and soil texture. He points out that, fundamentally, erosion is a mechanical process, the vital components of which are the forces which cause it, those which resist it, and the resulting motion of the eroded material. He conceived a natural slope as an open dynamic system tending to a steady state. A slope plot of unit width and of any desired segment of the length between the limits of a drainage divide and the axial stream channel at the base is considered to form the open system. Water and rock waste pass through the system only down-slope or vertically downward. The water and debris proceed cumulatively to the line of discharge at the slope base. When the system has achieved a steady state of operation, the rates at which materials enter, pass through and leave the system, become constant or independent of time, and the form of the system is stabilized. The nature of this steady state is determined by the relative magnitude of the forces of resistance and the forces tending to produce down-slope movement.

There are two major groups of opposed forces: those which tend to produce movement (fluid impacts, absorption of water by colloids, hydrolysis of silicate materials, expansion, contraction, etc.) and those which tend to resist movement (intergrain friction in the coarse sediments, capillary film cohesion in silts and clays, resistance of plant roots, stems, litter, etc.). These two groups of opposing forces may be formed into a dimensionless ratio with resistive forces in the denominator. When the force ratio exceeds unity, entrainment will set in and, in general, the higher the ratio the more rapid the rate of erosion.

Strahler (17), who used the work of Horton (5) as the starting point of his analysis, has in a series of mathematical stages evolved the formula $N_h = Q_s K_e S$, which, if applied to the region to be classified, will show which areas will erode under cultivation. N_h (the Horton number) summarises the erosional qualities of given slopes: Q_s is the run-off intensity, determined by the ratio of precipitation intensity to infiltration capacity; K_e is the erosion proportionality factor, determined by measuring the mass of soil removed per unit area of time (sediment yield) in relation to the eroding force (gained from data or run-off depth and slope); and S is the slope of the ground surface. The information needed to employ this formula is, therefore, angle of slope, length of slope, rainfall intensity, infiltration capacity, and sediment yield. The scientific knowledge needed to acquire and apply the data which are necessary for its application exists. Unfortunately, in many developing countries, no records are available on sedimentation, and sometimes not even on rainfall intensity. Accordingly, it is recommended that where the necessary data are present, the procedure outlined above should be followed; where they do not exist a survey should be conducted of the areas to be classified, and any signs of erosion should be recorded. If only certain areas have been utilised, and only from them can the necessary data be obtained, then the survey must be confined to those regions. Land is too vital a commodity for its use to be left to chance. The erosion survey is merely an expedient stop-gap, and every effort should be made to obtain the necessary apparatus and to lay down the required experiments in the country or region which is being classified.

Those areas which are susceptible to accelerated erosion will not be suitable for agriculture or grazing, and should be classified as being suitable only for tree crops.

The examination of soils is the ultimate stage in the attempt at land classification. Land which has not been classified as unproductive or suitable only for tree crops should then be considered. Soil profile, texture, structure, and soil depth should be recorded in the field, but judgements should be based not merely on these but on chemical analyses of the soil and on laboratory tests of plant growth and response to trace elements. After these analyses have been made the classifier will be in a position to decide, in view of the soil deficiencies, what land is unproductive, what areas are suitable only for tree growth, and what are suitable for tree growth, grazing and what may conveniently be called "arable agriculture". The broad classification will therefore be as follows:

Unproductive land (because of adverse climatic and soil characteristics). Land suitable only for tree growth (because of the limitations of topography and soil). Land suitable only for tree growth and grazing (because of soil factors). Land suitable for tree growth, grazing and arable agriculture.

Three points must be emphasized. First, the classification discussed above does not take into account special land-use practices, such as drainage, irrigation, contour planting and fertilizer application. The decision to employ such practices should be made at the planning stage, for economic and social considerations are involved.[1] Second, after the broad classification, which avoids excessive details, has been evolved, pilot schemes should be set up to test the classification. Third, there is no short-cut to the accumulation and processing of data. Much land has been mismanaged in the past because of the intuitive approach to land use. One of the objects of land classification is to eliminate this intuition.

4. RANGE OF LAND CLASSES

Only four land classes were delineated in the example which was used to illustrate the methodology described above. This is perhaps the simplest range of classification that it is possible to evolve. It is evident, however, that each of the productive classes may be further sub-divided and refined. The degree of refinement will depend upon the availability of data, as well as, and perhaps more important, the need for such refinement.

1/ See, e.g., Muthoo (11) and King (8).

It is urged, however, particularly in the developing countries, that the approach to land classification should be as uncomplicated as possible. Those wishing to examine other classifications with a wider range of land classes should refer, for example, to Klingebiel and Montgomery (10) where eight land classes are described, Canada (2) where seven have been categorized and U.S.A. (18) in which six classes have been identified.

5. CHECK LIST OF MINIMUM REQUIREMENTS FOR LAND CLASSIFICATION

A knowledge of the following factors is a pre-requisite to land classification.

Soil

Profile
Texture
Structure
Chemical reaction
Content of organic matter
Content of essential plant nutrients
Depth

Topography

Elevation
Degree of slope
Aspect

(A record should also be made regarding the nature of the general topography, i.e. is the land undulating, rugged, etc.)

Land condition

Erosion
Deposition
Depletion

Climate

Precipitation
Temperature
Climatic hazards

(Data which provide information on only average precipitation and average temperatures are often of limited usefulness and can be a snare and a delusion. What are required are maxima and minima precipitation and temperature data, and a knowledge of them over time, both within a year and for greater periods. In addition, a knowledge of a range of intensities of rainfall is also essential.)

6. SYNTHESIS

Finally, it should be emphasized that land classification is only a stage, albeit an important one, in the preparation of land-use plans. A sound land-use plan must be based on (i) an assessment of the physical potentialities of the land, i.e. a land classification, (ii) a socio-economic analysis of the nation's wants and resources which would lead to decisions on their allocation, and (iii) the provision of fiscal, institutional and legal measures for the implementation of this decision. All three elements are essential to success.

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II. THE INTEGRATED WATERSHED APPROACH FOR DEVELOPMENT PROJECT FORMULATION

Talat Eren

FAO, Thailand 1/

1. BACKGROUND

In the early 1960's, the United Nations Development Programme encouraged an "integrated" approach to development projects, but despite lengthy discussion of terms such as "integrated, comprehensive, multidisciplinary, basin-wide", etc., there have not been many actual examples of comprehensive projects on the ground.

This paper stems primarily from personal experience in managing an FAO field project in Thailand. The project was designed and has been executed with the philosophy of integrated land use as it relates to a developing country. The ideas given here are recommendations developed by the author.

In most developing countries, integration is the key to: (i) coordinate the use of limited funds and manpower; (ii) mobilize the rural population; and (iii) attain production from the land while protecting natural resources.

A watershed (synonymous with "catchment" or "basin", as used here) is made up of the natural resources in a basin, especially the water, soil and the vegetative factors. The comprehensive development of a basin so as to make productive use of all its natural resources and also protect them is termed "watershed management". This includes land improvements, rehabilitation and other technical works as well as the human considerations.

Historically, disastrous floods and droughts were accepted as natural calamities beyond the control of man. However, even some very old cultures constructed terraces and other works to control surface runoff. The famous Bamawe terraces in northern Luzon in the Philippines, for example, and those in Nepal, in the Mediterranean as well as in the Andes were not only an early achievement in watershed management but also a step towards the integration of human elements into a system of land management.

1/ FAO Project Manager for the Mae Sa Integrated Watershed and Forest Land Use Project, P.O. Box 1200, Chiang Mai, Thailand. The ideas and recommendations presented are essentially those of the author although some modifications and addition of figures have been made by the editor, FAO, Rome.

Figure 1. Farmers in Java constructing gully correction works to stop erosion on the Upper Solo River Basin. Part of the efforts on a World Food Programme project (WFP/FAO photograph by J. Bullard)

2. WATER AS THE INTEGRATOR

There is one common element in nearly every scheme of land development - an increased demand for water. Higher economic development invariably brings about higher water use. Consequently, the proper management of water resources is an essential component of development. From another viewpoint, water is the best index of "watershed management", that is, if a basin is properly managed for water, then it is also likely to be properly managed in other ways. Water is an excellent monitoring mechanism.

3. FACTORS IN INTEGRATION

There are essentially three factors to consider in initiating integrated development efforts: (a) the existing level of development, from a technical viewpoint; (b) the local social structure and human behavioural patterns and (c) the prevailing economic conditions.

In those countries having large rural populations with high growth rates, agriculture is typically poorly developed and technical know-how is low. Differences in production are related more to the size of land holdings than to modern techniques. Employment opportunities are poor, and farmers generally work at a subsistence level. The social structure and behaviour patterns are very primitive, and superstition may prevail. Traditional or local rules can be very strong. There is an inherent resistance to innovations. Large families are necessary as labour units. Obviously the social factors may be more of a restraint than the technical problems.

4. HOW TO INTEGRATE? AN EXAMPLE

The integration strategy for a watershed can be carried out by various procedures. The approach described here is but one example. It is underscored that it is only an example and not a universal blueprint.

A resource survey is the first step. The survey or inventory attempts to answer the question of the supply and demand for resources both natural and human resources. Depending upon the area involved, a survey may include: soil surveys, land capability/suitability classifications, forest and other vegetation inventories, erosion appraisals, flood and torrent information, streamflow and climatic characteristics, water use or other parameters, as needed. A number of factors that should possibly be considered for a socio-economic survey are listed in Table 1.

Table 1

Some parameters to evaluate in a socio-economic survey of a watershed (i.e., a basin)

Population census and description	
total population	rate of growth
sex ratios	migration patterns
age structure	
Behavioural and social characteristics	
family pattern	reaction to innovation
family size	educational level
traditions	religious sects
taboos	work ethics
details on communal administration	health schemes
farm/village organizations	forestry organizations
Economic and marketing factors	
land tenure patterns	marketing arrangements
patterns of cultivation	crop surveys
farming practices	input/output and yields of crops
shifting cultivation	labour, settled, migrant
transport systems	local/export use
forest inventories/descriptions	range and grazing surveys
industry (also for forestry)	
forest fire hazards and protection	

A few main points should be highlighted:

(i) the purpose of any data collection scheme must be exceptionally clear from the start;

(ii) effort should be directed to selecting a minimum number of parameters or, better still, indices to describe the existing conditions;

(iii) the sampling design and analytical techniques to be used should be established prior to data collection.

5. PREPARATION OF THE "INTEGRATED WATERSHED DEVELOPMENT PLAN"

An integrated watershed plan, including technical as well as the human aspects, is drawn up on the basis of the inventory. The analysis for each parameter normally should describe:

(i) the present status or conditions (e.g. good, poor, etc.)

(ii) the present trend (up, down, deteriorating, etc.)

(iii) the potential (development opportunity for the resource, likely future trends, potential problems, etc.)

Integrated planning should be a multi-disciplinary effort, which is difficult since this forces each participant to look beyond his own discipline. A "matrix" table or some of the other techniques described by Teller in his paper in this publication can be useful.

The watershed plan should be prepared on the basis on the following maps:

(a) A topographic base map prepared from existing aerial photographs (the most suitable scale is often 1:10 000). Smaller or larger scales can also be used, depending upon details needed.

(b) A slope map with, say, 0-5, 5-15, 15-35, 35-85 and "over 85 percent" slope intervals.

(c) A soil and land capability map which may be a combination of soil types, depths or other details with slope scale and degree of soil management intensity (for further guidelines and concepts, see the paper by King in this publication).

(d) An erosion and site degradation map showing the degree, size and stage of degradation as well as their causes, if possible.

(e) A vegetative cover map, including the type of native vegetation and permanent, perennial and annual crops.

(f) A land use and ownership map. A land use planning map should show the potential land uses as well as the existing land uses. A watershed development plan is drawn up from this information.

A watershed development plan should:

(a) give highest priority to the stabilization of subsistance agriculture and the implementation of soil and water conservation;

(b) employ labour intensive methods (where feasible) for land development, to provide immediate income for the people affected;

(c) pay rewards to those who use conservation measures on their own land; subsidies in terms of credit or loans can be very effective;

(d) provide for as many quick-cash activities as possible (e.g. handicrafts, poultry raising and animal husbandry) to offset time lost before farming can be fully productive;

(e) intensify technical assistance and extension in areas where conservation is not well known.

Figure 2. Local advisors and FAO specialists working with local technicians to demonstrate the use of a surveying instrument for installing contour ploughing to check erosion (FAO photograph, Jamaica).

6. INFRASTRUCTURES

Development of the natural and human resources in tandem is not possible without: improvements in communication, transportation, health and education schemes; a working mass information media as well as institutional support; a watershed development policy (supported by legislation) and an informed administration. These developments should be designed to build up the confidence of the people affected. To achieve such an infrastructur developments and institutions takes persuasion and demonstration.

7. DECENTRALIZATION

Decentralization is particularly important if a comprehensive watershed development plan is to be carried out on a regional basis, especially in remote areas. No central body can efficiently govern a development project which requires knowledge of local conditions, demands immediate decisions and depends on contact with the local people. The administration of projects, therefore, should be delegated to regional organizations with adequate autonomy and self-sufficiency in staff and equipment.

Coordination is essential at national, regional and field levels. National level coordination should deal mainly with development policy, legislation, institutional improvements, market promotion, subsidies, credits and other incentives, but only after careful analysis of regional requirements. Emphasis should be on regional development.

Regional level coordination should concentrate on planning and on developing work programmes, taking care to assign authority to the departments and agencies concerned.

Local level coordination should concentrate on the efficient use of the expertise and equipment available.

8. ACTION PROGRAMMES

The implementation of a programme of watershed development depends on the objectives of a project. Although these vary from one watershed to the next, certain features are common to almost every integrated watershed approach especially in the developing countries. First, each zone of land should be delineated by an interdisciplinary team. The team should tour the watershed with a person or committee representing the village or area concerned, to make field interpretations.

A land allocation policy can be determined and the areas proposed for each category of land use may be shown. After adjustments or revisions of the plan, the team and village representatives may want to break down the various land use categories into family-sized units. Cooperating farmers may then work with the relevant experts to develop the land allocated to them for its proposed use.

III.

ENVIRONMENTAL IMPACT ANALYSIS AND FORESTRY ACTIVITIES

by

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Unesco

1. INTRODUCTION

Responsible as he is for the multiple-use management of a renewable living resource and of its related environment, the forest land manager must be concerned with the potential impacts of his decisions on the interrelated processes which assure the proper functioning of that environment.

Research has made considerable progress in explaining and quantifying many of these processes, yet the heterogeneity of forest environments still makes it difficult to predict with any precision what will occur as the result of a specific proposed action at a given site. In many parts of the world today, management decisions concerning such actions as large-scale logging, road construction or recreation development, are still made without regard to their consequences in terms of processes such as soil erosion, nutrient loss or water pollution.

In many of the world's more developed nations, public knowledge and concern about the environment is now so great that decision-makers are obliged to show clearly what the effects of proposed land use activities will be, particularly where publicly-owned land is concerned. In many cases the public is insisting on the consideration of alternative courses of action, which may have a less detrimental environmental impact. While vast areas of the world's forests continue to be exploited and destroyed for immediate profit alone, there are signs that both professional and public concern will continue to grow, and that the forest land manager will be increasingly forced to consider not only the wider impacts of his decisions, but also the necessary balance between development and conservation.

2. ENVIRONMENTAL IMPACT ANALYSES

In many countries today, dwindling resources are subject to ever-increasing demands by either a more numerous or a more affluent population. In order to plan for a well-balanced middle course between the two unacceptable extremes of indiscriminate resource utilization and total resource conservation, the decision-maker must obviously have the best available facts at hand - how will a proposed activity affect a given environment ? The process of trying to find the answer to this question has come to be known as environmental impact analysis 2/ and is commonly carried out through the formulation of an environmental impact statement.

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2/ For a comprehensive treatment of the subject, see Munn 1975.

The point should not have to be stressed that the purpose of environmental impact assessment is to minimize adverse impacts rather than to suppress economic activity. However, fears of the latter are still expressed, for a variety of motives, in both industrialized and developing countries. The plea of the more rational environmentalist is that decisions be based on fact rather than on emotion, that development be based on a knowledge of resource capability, and that benefits and costs be evaluated across as broad a spectrum as possible, to include the long as well as the short term, the indirect as well as the direct consequences and that a full range of available alternatives be included in the analysis.

Although the primary purpose of environmental impact analysis is to provide the decision-maker with factual and predictive data which will make his decisions more objective, the statement which is produced can serve other useful purposes. It may merely be used to establish the existing environmental conditions in an area; it can certainly improve both short and long term planning capability for both development and conservation; it can provide legal "ammunition" where there is a possibility of litigation and, of course, it may fulfil any legal obligations which exist.

The philosophy and methodologies of modern environmental impact analysis were beginning to be developed during the middle and late 1960's, when a few countries began to realise that uncontrolled resource utilization and development could not continue indefinitely, and that stronger public control had become necessary. In the United States, for instance, the 1970 National Environmental Policy Act (NEPA) obliged public agencies to prepare environmental impact statements prior to initiating any large-scale action which may have significant environmental consequences.

Many other countries have now adopted similar regulations, although, on a world-wide scale, the areas without adequate regulation of development activities are still unfortunately in the majority.

3. SCOPE AND CONTENT OF ENVIRONMENTAL IMPACT ANALYSIS

Obviously not all operations associated with forest resource management will be of sufficient size or have such significant environmental impact as to warrant the preparation of an impact statement. A responsible manager must decide when and where an environmental impact analysis should be carried out, and whether its cost is justified by the likely impact of the action being considered.

The U.S. Forest Service Manual (1974) states that "... environmental statements should be prepared ... for Federal actions significantly affecting the quality of the human environment. Such "significant effect" may include actions which have both beneficial and detrimental effects ... The following categories of criteria should be considered:

- Degree of ecosystem disturbance (both on-site and off-site effects);

- Irreversible effects on basic resources (short term versus long term commitments);

- Cumulative effects of many small actions;

- Chain reactions or secondary effects of interrelated activities;

- National as opposed to only local importance;

- Uniqueness or rareness of resource;

- Anticipated public interest."

The contents of an environmental impact statement will obviously vary with the nature and scope of the analysis undertaken, and will vary from small, relatively simple, local actions and impacts to large-scale, complex development projects with potential national or even international impacts. The points to be covered in the analysis should therefore be regarded as indicative rather than either obligatory or exhaustive. They are taken from the Guidelines recommended by the U.S. Council of Environmental Quality (U.S. Congress, 1973).

4. POINTS TO BE COVERED IN IMPACT STATEMENTS

These should include:

- A description of the proposed action, a statement of its purposes and a description of the environment affected.

- The relationship of the proposed action to land use plans, policies and controls for the affected area.

- The probable impact of the proposed action on the environment, including both positive and negative effects and secondary or indirect, as well as primary or direct consequences.

- Alternatives to the proposed action (including no action, which may also have environmental consequences).

- Any proposed environmental effects which cannot be avoided, and are therefore predictable.

- Probabilistic effects which are predictable statistically only.

- The relationship between local, short-term uses of man's environment and the maintenance and enhancement of long-term productivity.

- Any irreversible and irretrievable commitments of resources that would be involved in the proposed action, should it be implemented.

- An indication of what other interests and considerations are thought to offset the adverse environmental effects of the proposed action.

5. PREPARING THE ANALYSIS

There are, of course, considerably varying degrees of difficulty related to each of the components outlined above. Whereas some parts are largely descriptive and can be presented in narrative form (e.g. description of proposed action; statement of purpose; description of environment affected; relationship of proposed action to land use plans and policies), the actual assessment of the probable impact is likely to be far more complex. If a comparison of alternatives is involved, as it generally should be, quantification of the probable impacts is essential.

The task would still be relatively straightforward if the relationships between environmental impacts and their corresponding effects were well understood. For instance, if, for a given forest area, it was known that the clearfelling of x percent of the stand would result in an increase of y centimetres of runoff, the likely hydrologic impact of removing any other proportion of the stand would be easier to estimate. Unfortunately, a clear quantitative understanding of the impacts which land use changes have on natural ecosystem processes is the exception rather than the rule. Even where figures are available for a particular area, extrapolation to larger or smaller units of land and to other soils, geological formations, climates or social customs, is generally risky at best.

Nevertheless, as in most other walks of life, the environmental analyst must do the best he can with the resources and knowledge available. In many countries there is, in fact, a great deal of information already available, particularly in areas or disciplines which have been of long-standing interest. New research may therefore be very limited or entirely unnecessary. The application of some of the more common pesticides to certain agricultural crops is a case in point.

However, when new impacts are foreseen, such as the application of a new chemical in a forest or grassland, or the application of a relatively untested technology (e.g. the introduction of exotic species), difficult decisions must be made regarding the magnitude and the duration of the financial and human resources which will be allocated for research and impact analysis. No general rules are possible here, except that the cost of the research and analysis must obviously bear a reasonable relationship to the cost of the proposed action and its anticipated benefits. A 'rule of thumb' figure of 10% of project costs has been suggested for the cost of environmental impact assessment, including relatively short-term research.

6. IDENTIFICATION OF IMPACTS AND LIKELY EFFECTS

As we have seen, any impact analysis must include a description of both the environment to be affected and the proposed actions on it. The latter are generally more readily defined than the former, which may require considerable inter-disciplinary study before it can be adequately described.

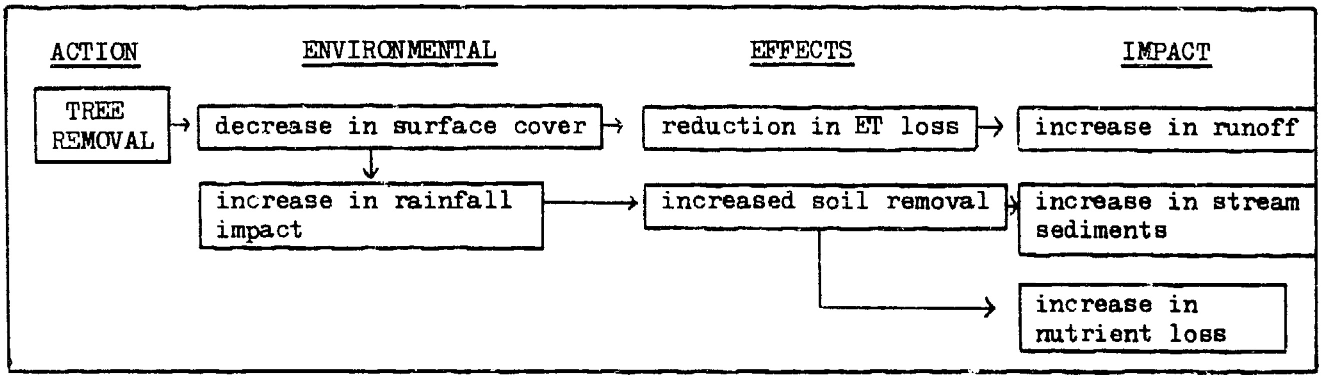
Of the three main methods of environment-impact identification (checklists, matrices and flow diagrams), the matrix, where actions are listed on one axis and impacts, as measured by selected impact indicators, on the other axis, is perhaps the most commonly used. An impact indicator is a variable which responds to an impact, preferably in a quantifiable manner, e.g. suspended sediment, pH and DO (dissolved oxygen) are impact indicators of water quality; SO_2 and ozone concentration are indicators of air quality. Some indicators are only quantifiable by ranking, e.g. absent, low, medium, high.

Checklists alone do not show relationships between action and effect very well and may result in the omission of important impacts more readily than the other techniques. Flow diagrams, which are actually simple word or compartment models, do show interactions readily (perhaps better than matrices, which are limited to two axes), but require a somewhat better understanding of relationships than does a simple matrix. Table 1 illustrates part of a simple check list, while Table 2 shows part of a simple flow chart.

Table 1: Partial checklist of possible logging impact identification

Action	Effect	Environmental Impact
Removal of trees	- reduction of leaf area and interception	- increased runoff
	- reduction of ET loss	
	- deterioration in soil structure and reduced infiltration	- increased soil loss and sediment in stream
	- removal of nutrients from the site	- reduction of soil nutrient status

Table 2: Partial flow chart for logging impact identification



The reader will note the importance of rational intuitive thinking, prior knowledge and at least a fundamental understanding of environmental processes, so that the right questions can even be asked. Most environmental impact analyses must be completed in a relatively short time and with a limited budget, so that the analyst will be hard put to accurately predict the magnitude of even the impacts which are expected. Thus, those which are entirely unexpected may well not even be identified for study. The classic linking of DDT in birds with eggshell thickness is a case in point.

7. PREDICTION OF IMPACTS

Once the environmental components and their impact indicators have been identified, the magnitude of the impacts must be predicted, preferably in quantitative terms, but in practice more often qualitatively. Unless new research is undertaken, all predictions must be based on the existing "state-of-the-art" in the disciplines involved, and on a scientific approach in the application of this knowledge to the particular situation being examined.

For example, the hydrologic impact of eradicating an area of unwanted vegetation with hormone defoliants may be estimated by comparing the site conditions with those which existed in a nearby watershed research project where similar vegetation was removed. In this case the area of defoliated vegetation is the important variable for comparison, rather than the nature of the chemical used. On the other hand, the duration of the defoliant in the soil, and its movement into the adjacent stream, may be predicted by using data from a second study at a different site. In this case the nature of the chemical is the important variable to be compared with the previous study. While the available information should be collected from all possible sources, the extrapolation of these data must be undertaken with great care.

The development and continual refinement of mathematical models will, of course, considerably facilitate the environmental analysts' task. Thus, models which relate impacting variables (e.g. area of forest cleared, tons of coal burned) to impact indicators (e.g. sediment concentration in stream, SO_2 concentration in air) and environmental variables (e.g. slope of ground, annual precipitation, wind speed), will enable the analyst to simulate a range of hypothetical conditions and to obtain quantitative measures of the resulting environmental changes. Numerous such models are already in existence in fields such as hydrology, water quality and air quality. Frequently the scientists who developed them are only too pleased to assist prospective environmental analysts.

In many cases new research must be undertaken before an untested technology is used. This is particularly true when new substances are released to the environment, or when new impacts are likely to cover large areas or to affect valuable resources. As funds are always a limiting factor, difficult decisions are often required concerning the part of the environment to be studied, e.g. should it be the water, the soil, the plants, the animals or humans ? Objective decisions are easier to make in such cases if uniform criteria are applied in the selection of research topics, e.g. prevalence of the organism on the impact area, ecological and economic importance, uniqueness, degree of public interest, etc. Simple numerical ranks can even be calculated by assigning levels (e.g. absent, slight, moderate, great) to each criterion and obtaining sums or means which can be ranked in order of priority.

8. METHODS OF IMPACT ANALYSIS

In recent years several impact analysis methodologies have been evolved. Three of these, the Leopold Matrix (Leopold, L.B. et al. 1971), the Overlay Technique (McHarg, 1969) and the Battelle Environmental Evaluation System (Dee et al., 1972), have been fairly widely adopted. Their basic characteristics are outlined below. The Leopold Matrix, one of the earliest and simplest techniques of impact analysis, essentially ensures that the interactions between a list of environmental actions and other list of environmental 'characteristics' and 'conditions' will be considered in an orderly manner.

The actions, which are listed across the top, or horizontal axis, of the matrix, include:

Type of Action	Example
A. Modification of regime	habitat modification
B. Land transformation and construction	airports, roads
C. Resource extraction	timber harvest, fishing
D. Processing	energy generation, oil refining
E. Land alteration	strip mining, erosion control
F. Resource renewal	reforestation, groundwater recharge
G. Changes in traffic	automobiles, railways
H. Waste emplacement and treatment	effluent discharge, landfill
I. Chemical treatment	fertilization and pesticide application
J. Accidents	oil spills, explosions

The vertical axis lists environmental characteristics or conditions which may be affected by the actions listed above. These are arranged in the four major categories of:

	Example
A. Physical and chemical characteristics	air or water quality
B. Biological conditions	flora and fauna
C. Cultural factors	aesthetics, recreation
D. Ecological relationships	eutrophication, food chains

There must obviously be overlaps, or 'double counting' between the interactions. For instance, impacts on physical and chemical characteristics will also be involved in ecological relationships. However, this should not prove to be a serious handicap.

In boxes at each interaction of the matrix, where an impact is judged to be possible, two figures are inserted showing, on a scale of 1 to 10, the magnitude and the importance of the possible impact (Figure 1). The statement which accompanies the matrix is a discussion of the significant impacts - those columns and rows with large numbers of boxes marked and individual boxes with the larger numbers.

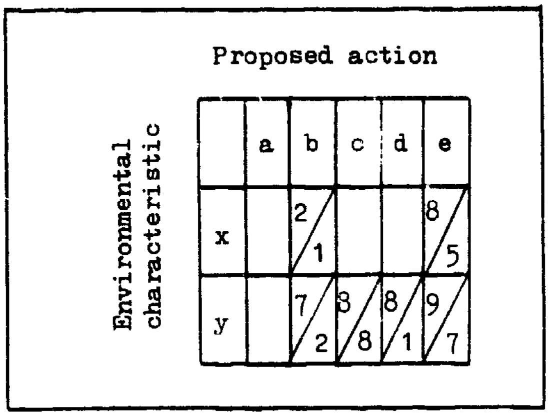


Figure 1. The Leopold Matrix

The main advantages of the matrix method are that it is relatively simple to understand and use, can be adapted to a wide range of impacts, makes provision for both magnitude and importance of impacts, and gives a good visual picture of the situation.

Its major disadvantages are: it does not differentiate sufficiently between processes or activities (e.g. eutrophication, swimming) and indicators of state (e.g. nitrogen concentration, coliform count); it does not focus attention on the most critical human concerns; it makes no provision for degree of uncertainty; it is not very objective (each assessor developes his own ranking system). In spite of these shortcomings, it is perhaps still the most satisfactory method for small-scale studies which are carried out with limited resources, by relatively inexperienced personnel.

The 'overlay' technique of impact assessment consists essentially in mapping geographically - based features and their related anticipated impacts.

> "A series of transparencies is used to identify, predict, assign relative significance to, and communicate impacts in a geographical reference frame larger in scale than a localized action would require." (Munn, 1975).

The method is best suited to the selection of minimum-impact corridors, such as highways, pipelines, railways and power transmission lines. One or more types of environmental impact is mapped on each transparency, the total being limited to about 10. For instance, in selecting a desirable road right-of-way, one map may feature density of existing human habitation (perhaps in a number of categories such as high, medium, low, or in actual quantitative density classes). A second map may show cost of right-of-way acquisition (in a number of cost classes). A third map may show severity of disruption to wildlife and fisheries values; a fourth may indicate impact on productivity of agricultural land.

Finally, the total impact of the selected factors can be shown visually or quantitatively on every land unit of desired size. The desired corridor can then be selected along the 'minimum impact' route. Computer programmes are available to display the desired map information and can be adapted readily where the necessary hardware and technical know-how is available.

The method is selective, as only a limited number of impacts can be considered; while spacial patterns are well defined, magnitudes of effects are more difficult to show; uncertainty and extreme impacts with small probability are difficult to illustrate. Nevertheless, the method is useful for large regional developments and for corridor selection problems.

9. THE BATTELLE ENVIRONMENTAL EVALUATION SYSTEM

The Battelle Environmental Evaluation System was developed specifically to evaluate the impacts of water resource developments, but it has wide application in natural resource fields in general.

One of the most difficult problems of impact analysis is to compare in a quantitative and objective manner the impacts observed or predicted for various parts of the total environment. The ranking of a number of alternative action possibilities, or the comparison of environmental conditions "with" and "without" a given activity, also require that impacts be measured in comparable or commensurate units.

To account for the availability of different 'levels' of information, the system is hierarchical in nature, ranging from the most generic level of four environmental 'categories' to the most detailed level of environmental 'indicators'. (See Table 3).

The procedure essentially consists of three main steps, the third level of organization (environmental parameters) being used as the key level for analysis:

a) By the use of a value function, all parameter estimates are transformed into their corresponding level of environmental quality, which ranges from 0 to 1 (see Fig. 2).

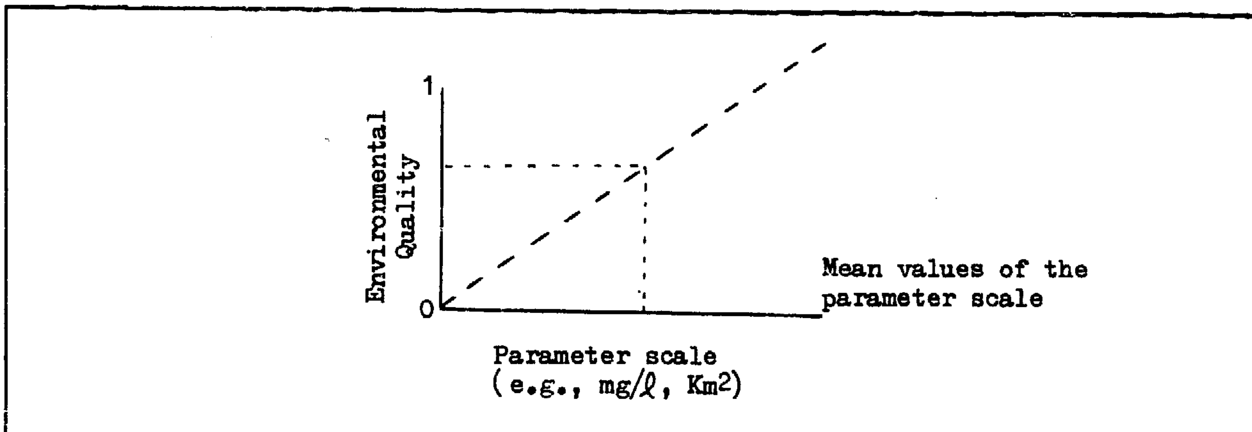


Figure 2. Typical value function used in Battelle Evaluation System

b) The relative importance of various parameters has been expressed in Parameter Importance Units (PIU's) - see Table 3. Although these units provide the necessary uniformity between projects, they do place a somewhat empirical constraint on the method as a whole.

Table 3: BATTELLE ENVIRONMENTAL EVALUATION SYSTEM
(Dee et al., 1972. Reference 1)

ENVIRONMENTAL IMPACT

Ecology 240

Species and Populations

Terrestrial
- (14) Browsers and grazers
- (14) Crops
- (14) Natural vegetation
- (14) Pest species
- (14) Upland game birds

Aquatic
- (14) Commercial fisheries
- (14) Natural vegetation
- (14) Pest species
- (14) Sport fish
- (14) Waterfowl

[140]

Habitats and Communities

Terrestrial
- (12) Food web index
- (12) Land use
- (12) Rare and endangered species
- (14) Species diversity

Aquatic
- (12) Food web index
- (12) Rare and endangered species
- (12) River characteristics
- (14) Species diversity

[100]

Ecosystems

Descriptive only

Environmental Pollution 402

Water Pollution
- (20) Basin hydrologic loss
- (25) BOD
- (31) Dissolved oxygen
- (18) Fecal coliforms
- (22) Inorganic carbon
- (25) Inorganic nitrogen
- (28) Inorganic phosphate
- (16) Pesticides
- (18) pH
- (28) Stream flow variation
- (28) Temperature
- (25) Total dissolved solids
- (14) Toxic substances
- (20) Turbidity

[318]

Air Pollution
- (5) Carbon monoxide
- (5) Hydrocarbons
- (10) Nitrogen oxides
- (12) Particulate matter
- (5) Photochemical oxidants
- (10) Sulphur oxides
- (5) Other

[52]

Land Pollution
- (14) Land use
- (14) Soil erosion

[28]

Noise Pollution
- (4) Noise

[4]

Aesthetics 153

Land
- (6) Geologic surface material
- (16) Relief and topographic character
- (10) Width and alignment

[32]

Air
- (3) Odour and visual
- (2) Sounds

[5]

Water
- (10) Appearance of water
- (16) Land and water interface
- (6) Odour and floating materials
- (10) Water surface area
- (10) Wooded and geologic shoreline

[52]

Biota
- (5) Animals - domestic
- (5) Animals - wild
- (9) Diversity of vegetation types
- (5) Variety within vegetation types

[24]

Man-made Objects
- (10) Man-made objects

[10]

Composition
- (15) Composite effect
- (15) Unique composition

[30]

Human Interest 205

Educational/Scientific Packages
- (13) Archeological
- (13) Ecological
- (11) Geological
- (11) Hydrological

[48]

Historical Packages
- (11) Architecture and styles
- (11) Events
- (11) Persons
- (11) Religions and cultures
- (11) Adventure value

[55]

Cultures
- (14) Indians
- (7) Other ethnic groups
- (7) Religious groups

[28]

Mood/Atmosphere
- (11) Awe-inspiration
- (11) Isolation/solitude
- (4) Mystery
- (11) "Oneness" with nature

[37]

Life Patterns
- (13) Employment opportunities
- (13) Housing
- (11) Social interactions

[37]

Legend

( ) Parameter Importance Units

[ ] Total

c) The Environmental Impact Unit (EIU) of action on a given parameter is calculated by multiplying the Parameter Importance Unit (PIU) from step (b) above, by the Environmental Quality (EQ) calculated in step (a) above, i.e. (EIU) = (PIU) x (EQ).

The total EIU's for each major category (ecology, environmental pollution aesthetics and human interest) can then be compared for different project alternatives, or for "with" and "without" a given project.

The major difficulty naturally arises in deriving the value function of a given parameter (step (a) above), though qualitative ranks may be used here in the absence of real data (i.e. zero, low, average, high).

The Battelle System has a number of advantages, assuming that both technical data and human resources are available for its use. The analyst may use any level of detail which is available; the system is fairly objective, in that it uses standardized parameter weights and generally available technical data to calculate impact indices. Disadvantages include the fact that some impacts may be measured more than once in different categories and that interactions and synergistic effects are not evaluated. However, it does incorporate a 'red flag' or warning system to alert the analyst to potentially serious impacts.

10. CONCLUSION

There is no 'best' method of carrying out an environmental impact analysis. As projects vary in size, significance and complexity, different methods of analysis, or combinations of methods, will be required. As in other fields, experience is the best teacher and neophyte analysts should not be deterred by lack of knowledge or experience at the outset. However, the necessity for an interdisciplinary team approach cannot be overemphasized, and the need for expertise in a number of fields may well serve to promote better co-operation between groups of scientists or agencies which previously tended to work in relative isolation.

Even where no legal compulsion exists to force the preparation of environmental impact statements, today's natural resource manager should take it upon himself to ensure that the adverse environmental impacts of his decisions and activities are minimized. While there will be many cases where consideration of short-term benefit or profit for an individual or for a small number of people, will be allowed to over-ride the wider, longer-term benefits of careful resource utilization, a conscious striving for environmental quality has certainly become one of the most essential ingredients of natural resource management.

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IV.

EVALUATING RESULTS OF CONSERVATION PROJECTS

by

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1. EVALUATIONS OF RESULTS

Soil conservation and restoration measures can be classified under two headings:

i) those essentially confined to cultivation techniques, which serve to restore or enhance productivity on a short-term basis; and

ii) those involving longer-term erosion control projects which are designed to prevent the permanent and irreversible deterioration of soil productivity.

Measures of the first type cost relatively little and are obviously in the best interest of farmers and may be left to the farmers' individual initiative; those of the second type entail heavy investment, but have a long-term effect and produce community-wide benefits. In this latter case erosion control is considered a problem of interest to society in general.

In principle, public authorities could confine their obligation to the second type of activities without expection of short-term profits or financial returns. However, a comprehensive erosion-control programme can only attain full efficiency when the entire complex is considered, including the activities of farmers whose interests lie mainly in short-term productivity.

The public and private interests are inextricably linked. Their social, economic and financial benefits must therefore be judged in an overall perspective as a result of both rural land development and agricultural development projects.

2. EVALUATION OF ECONOMIC RETURNS

2.1 Evaluation Approaches

The economic profitability of a soil conservation project may be evaluated at different stages in the progress of the project as:

a) a priori, to estimate the project's profitability as compared with other possible investments and to secure financing, usually from resources outside the country.

1/ This paper originally appeared in the French language as Chapter III in the book "Conservation des sols du sud du Sahara", which is part of the CTFT series "Techniques rurales en Afrique". The translation into English was made by FAO in Rome and the material is used courtesy of CTFT, 45 bis Avenue de la Belle Gabrielle, 94130 Nogent-sur-Marne (Val-de-Marne), France. Special appreciation is extended to Mr. P. Goujon, Directeur d'Etudes, for his cooperation.

b) a posteriori, to check against initial estimates and to determine goals which still need to be achieved and to seek additional financing or permit national authorities to take over when deemed advisable.

Economic profitability, in the broadest sense, always shows a positive balance, even if appraised at each successive stage. Thus, it can be used as a platform to gain public support. Nevertheless, in economics, the situation must be reviewed constantly, with a view toward possible modification and improvement of action, including the consideration of all possible alternatives and combinations of production and input factors. In this way results are gauged against a much broader background ranging from such things as soil capability studies to marketing research.

In this paper, we shall confine ourselves to a description of the two most direct aspects of economic evaluation: (i) cost/benefit analysis; (ii) definition of applicable profitability criteria.

2.2 Cost/Benefit Analysis

Whatever profitability or benefits criteria are selected, their use requires preliminary costing and estimates of returns from the project. Obviously, the accuracy of such estimates is greater when done after the project is completed if done in advance. Nevertheless, baseline data must be compiled to limit survey costs and enhance its accuracy.

2.2.1 Costing

Costs fall under two headings: (i) investment and installation costs, and (ii) upkeep and operating costs.

Investments and installation costs include those of:

a) losses due to demolition of existing facilities, if necessary;

b) land purchase or indemnification for appropriation;

c) constructing erosion control projects (materials, energy, labour, including the value of nonpaid labour);

d) resettlement costs, in cases where relocation of population are necessary.

Maintenance and operation costs, assessed for an average year, comprise:

a) cost of upkeep of the erosion control projects, including remunderation of non-wage labour;

b) operating costs (manpower training, instruction, extension work, overheads, etc.);

c) costs to farmers, including wages for extra labour required to work a larger land area or costs of changeover in farming systems.

Sufficiently accurate costing of a) and b) above can be requested directly from the management agency. However, the assessment of farming costs must be obtained by a survey of the financial outlay and labour time of farmers, which requires rather elaborate methods of data collection to cover both the pre-investment period and the current operation period.

2.2.2 Receipts or income

Direct returns from the operation correspond essentially to the additional gross product ascribable to the project. Two inventories are needed, one conducted prior to initiating the project and the other after the project has produced results. Both surveys should appraise the agricultural and forage production potential of the zone, the changes in which will have a direct impact on stock-raising.

Depending upon the scope of the project and the means available the appraisal can be done either by statistical methods or by simpler estimation methods (e.g., land area measurement by aerial photography, weighing the quantity of seed used or the number of plants per ha, forecasting agricultural crops by the method of measuring yields from sampling plots, starting from volume of crops either stored, shipped or marketed, etc.)

The finding of the two inventories must also take into account exceptional factors (weather, etc.) as well, in order to determine the average increase in annual gross product actually attributable to improvements made by the project.

Insofar as possible, account must be taken not only of the increase in the gross product over the original amount but also of the presumable losses that might have occurred from the soil degradation had there been no project.

2.3 Criteria for Assessing Profitability

The economic profitability of a rehabilitation or conservation project should be appraised by the most direct means first, and then the bases for judgement should be gradually broadened. One good criterion for assessment of a long-term investment is the profits realized.

2.3.1 Profits realized

For an initial investment (I) covering a period of 0 to n years with returns (R) against expenditures (E), assuming that the internal rate of return (i) remains constant, 1/ the profits realized are computed by the following:

$$P = -I + \frac{R_1 - E_1}{1 - i} + \frac{R_2 - E_2}{(1 + i)^2} + \cdots\cdots \frac{R_n - E_n}{(1 + i)^n}$$

Now in a soil conservation and restoration project, at least when the end purpose is the improvement of agricultural and livestock production, the assumption can be made that the levels of returns and expenditures will remain relatively constant from one year to the next, once the project becomes operational.

Furthermore, to the extent that regular maintenance of the erosion control network is ensured, the life-span of the investment is assumed to be practically unlimited. Since land often has no stated value, there is no other way to assess the benefits derived from soil conservation than by running a sequence of the extra production attributed to the project were it extended over an infinite time.

Assuming constant net returns, and a number of years reaching infinity, the profits realised amount to, at the outside:

$$P = -I + \frac{R - E}{i}$$

The next step should be to select an internal rate of return (i) which corresponds to the type of works to be undertaken and the general economic conditions of the country.

1/ Editor's Note: The internal rate of return may be defined as the rate of discount (interest) which makes the present value of the entire stream of future net profits from the investment equal to the cost of the investment.

In order to avoid theoretical problems raised by such a choice it is necessary to determine what rate cancels the profits realised by comparing rates adopted for other projects. The internal financial rate thus calculated helps decision making.

The internal rate of return corresponds neither to the interest rate applied to the funds invested, nor to the prevailing market interest rate. It indicates the relative importance of future in relating to current ones.

For public investments in France this rate, according to the "Plan", is 7 percent (the actual rate is 11 percent). In Africa it may reach 15 percent or more. 1/

Note that in calculating the profits realised, the same rate is used for both current net returns and its investment spread over several years.

2.3.2 Profits realised, taking added value into account

The calculation of profits realised makes it possible to get an idea of returns on invested capital and the profitability of the project.

Very possibly, the net profit of the management agency and the increase in income of farmers will not be sufficient to make the investment a profitable one. There may even be a loss. This does not mean that the project is not worthwhile if seen from a broader standpoint that considers returns on all factors of production.

From this standpoint the term "annual net returns" are replaced in the formula for profits realised by the term "added value" which includes, in addition to the net returns, remuneration for labour (including non-wage labour) as well as any possible taxes. The profits, thus realised, are shown by the formula:

$$P = -I + \frac{VA}{i}$$

Additional "added value" that expresses the increase in gross national product due to the land management scheme may be based on estimates of other partial criteria referred to capital. It gives a truer idea of the efficacy of the investment in terms of the number of workers or families affected by the project; it indicates the impact on the level of living, referred to land area, and it provides a scale for the agricultural yields obtained.

2.3.3 Indirect economic effects

The economic effects of any soil conservation and reclamation project actually go beyond those strictly pertaining to the project. Any assessment of results must also envisage various other economic benefits not all of which can be put into terms of crop production or income.

The benefits include:

- the effects of manpower training on new production and investment both pre- and post- project;
- the multiplier effect on income derived from income created by the project at the level of farms, transportation, marketing, the processing industries and other sectors of the economic supplying inputs;

1/ Editor's Note: These figures in the original French manuscript were prepared prior to recent economic changes; therefore, the values are now rather conservative. Internal rates of return of 20 percent or more are not unusual for development projects.

- the impact on the national balance of payments, which is particularly important in those cases where the balance suffers from a structural disequilibrium.

These benefits (which are only the obvious ones) are difficult to quantify, since their estimation presupposes some acquaintance with the expenditure/income strucutre of the various economical agents as well as with the functioning of many economic pathways. Little is known of the economic flow patterns in the developing countries, and what is known is only partial and discontinuous. This restricts evaluation of the impact of any particular investment on the overall economic system; nevertheless, it is still important to try by the best means possible to determine the impact of such investment.

3. ASSESSMENT OF RESULTS FROM THE SOCIOLOGICAL STANDPOINT

As with economic results, it is not possible to make only a posteriori study of the impact upon the human population of any development project when the investment and, to a lesser extent, the organization and functioning of the project have become irreversible. In fact, a soil conservation or land reclamation project may completely alter sociological patterns. The social changes should not be allowed to occur in chaotic fashion, but should be organized and fitted to the technological and economic changes. The sociological impact is not merely of statistics; it is also the principal means for making the project successful. Therefore, sociological impact studies should be done in three successive phases:

- an analysis of the human milieu and of sociological and organizational structures;

- a definition of norms, standards and ways and means for altering this milieu for immediate application;

- a critical analysis of changes in the original situation effected.

3.1 Analysis of the Human Milieu or Society

The appraisal of the traditional sociological milieu should be based on a series of surveys and research centred on the points outlined below.

As a rule such studies must be based on available documentation supplemented by field surveys conducted by psycho-sociologists. In some instances, rather rare ones, a preliminary statistical survey may be justified. 1/

3.1.1 Demographic and sociological features

- The total population of the area, the population structure (sex, age, ethnic groups, vocations or occupations, etc.) and future trends, in the light, on the one hand, of natural changes and, on the other hand, in anticipation of either spontaneous or organized population shifts or migrations;

- data on community life (clans, lineage, families); social stratification, the lines of authority and political organization; existing village communities, their composition (ethnic groupings, relationships, age groups, social status and political role of members) occupations and economic activities, their functioning (exercise of authority, relations between members) and their spatial distribution (definition of village lands).

1/ Editor's Note: The reader may also want to compare the parameters listed in Parts 3.1 and 3.2 which are orientated toward Africa to those recommended in the paper by Eren, which are drawn from his experience in Asia.

3.1.2 Land tenure structure

- definition of levels of land holdings (by tribes, class, individuals) and manners of land tenure (as property, or use rights);
- methods of acquisition, transmittal and alienation of land titles or rights;
- authorities on land tenure affairs and settlement of land disputes;
- relation between land rights and social, political and religious systems;
- farming practices (farming directly by holder, land leasing, share-cropping, etc.)

3.1.3 Farm structure

- size of farms and main features (area, number of farm workers, capital);
- organization of work (division of labour on farms, collective farming and individual farming);
- traditional crops, cultivation techniques and stockraising systems.

3.1.4 Attitudes and behaviour

- reactions of farmers to schemes or action projects launched or planned;
- Their understanding of and views on, social and economic progress (scale of values, expression of needs, etc.).

3.2 Definition of Standards and Means of Action upon this Milieu

Sociological research, whether conducted earlier or at the outset of the project, have more than the single goal of evaluating the milieu. Its purpose is also to lay the foundation for setting norms and goals and working out the means of altering the society. This is a prerequisite to the success of a project. Thus, demographic research on the migratory movements of people may involve problems of habitat, authority and the social life of people with different backgrounds. Solution to these problems must be sought in advance in order to avoid conflicts between ethnic groups or between new imigrés and settled land owners.

As regard land tenure, erosion control projects definitely increase land values. This may entail contradictory claims or may encourage speculation. Thus, before a project has started it is important to delimit the precise boundaries of the land area to be developed and to determine land titles and rights. The problem obviously will be different for different farms. It possibly may involve appropriation of individual land holdings, or there may be superimposition of collective and individual titles. In the second case, a possible solution is to declare the land to be developed part of the public domain.

The next step is to consolidate small plots and redistribute them, with due regard to the extent possible of well-founded rights and titles. Evicted land-owners should be compensated according to law. Contracts should be made with the new tenants. They should establish the conditions of land use, the manner of transmittal of land rights, maintenance costs and financial charges.

This offers the advantage of granting the people on the land the only use rights. Provisions should be made to withdraw these rights in case the landowner fails to comply with the contract.

Studies of human society, especially those of social structure and of the behaviour patterns of farmers should make it possible to decide what types of farming should be promoted and what types of organization (village groupings, collective farms) would be desirable.

Such research will also make it possible to:

- adapt the manpower training and extension work programme to the specific human milieu;

- decide for which zones and categories of farmers modernization efforts should be given top priority;

- discover enterprising people whose minds are open to innovation and who enjoy a certain amount of prestige or authority among the farmers, and on whom the project can depend for support; and

- create a management body in which farmer representatives and administrationb officers work together in supervising the maintenance and functioning of the project.

3.3 Critical Analysis of Changes Effected

Just as the social problems should be analyzed before the project is undertaken, so should options on organization match the technological options. It is advisable at the end of the project to make an analysis of its social and psychological impact.

The purposes of this analysis are to:

- measure results of the transformation of the human milieu (e.g., the settlement of nomads, the modernization of the farming system, etc.);

- assess the efficacy of the new organizational structures;

- poll opinion of the people involved and find ways of improving their collaboration.

The information gathered can be used to redress negative aspects and to eliminate any maladjustment due to traditional social behaviour or organizational structures.

4. EVALUATION OF RESULTS FROM THE FINANCIAL STANDPOINT

The study of financial profitability, in the strict sense of the term, is of little interest, as the principal purpose of a project is to foster development by increasing the efficiency of agriculture, rather than to launch a profitable financial venture.

Concern with financial profit-making must be relegated to second place where no private capital is invested in the project and the financing is carried by national authorities or by foreign aid. Apparently under these circumstances, the assessment of achievements must be thought of as an analysis of cost distribution among the various beneficiaries - the farmer, beneficiaries of the enhanced soil productivity and the national community, represented by the government of the nation, for whom the benefits are both long term and more widespread.

Since the government - which originally makes the decision to invest in the project - usually also undertakes the financing of the infrastructure and the paying off of any loans, it seems reasonable that most of the operational and maintenance costs be borne by the direct beneficiaries. 1/

1/ Note that since the life span of the investment is, in principle, unlimited the reconstitution of invested capital for renovation of the erosion control networks is not a matter of concern, provided they are maintained properly.

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The government's contribution, actually corresponding to the difference between the total cost and ability of the farmers to pay, thus seems a foregone conclusion. Since political will cannot change this in the foreseeable future, it is essential to carefully calculate this aspect of the financing from the beginning.

5. CONCLUSIONS

The methods of evaluation of any soil conservation project cannot be prescribed as a rigidly preconceived system. The most diverse of situations must be investigated and understood, sometimes with very limited means. Neither can such an investigation be expected to be very accurate since measurements can only be very approximate and the future can only be predicted with uncertainty. Yet some effort at evaluation - to the extent that it is not purely theoretical - is essential.

The achievements of any soil conservation project cannot be expressed in static figures, once and for all, but must be the basis for continuing dialectics; further action being decided on the basis of progress made.

6. FURTHER READING SUGGESTIONS

Reading the topic of agricultural investments of possible use to the reader may be found in a number of books. However, a paperback of particular interest may be: "Economic Analysis of Agricultural Projects" by J. Price Gittinger, The Economic Development Institute, International Bank for Reconstructional Development, 1972, reprinted 1973, The John Hopkins University Press, London or New York, 221 pp. FAO also has some guidelines but more farming oriented, such as "General Guidelines to the Analysis of Agricultural Production Projects", Agricultural Planning Studies No. 14, 1971.

1/ Note that since the life span of the investment is, in principle, unlimited the reconstitution of invested capital for renovation of the erosion control networks is not a matter of concern, provided they are maintained properly.

Figure 1. Building small bench terraces for reforestation in Morocco.

V.

APPLICATIONS OF REMOTE SENSING TO WATERSHED MANAGEMENT

by

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1. INTRODUCTION

Remote sensing from space started in 1960 with the launch of the first meteorological satellite, TIROS 1. Several generations of meteorological satellites have been flown in the intervening years that have been of some interest to the hydrologic community. Manned space flights began in the mid-1960's and special photography experiments revealed much useful information to a variety of interested earth scientists. Colour and black and white imagery of snowfields and surface water caught the interest of some hydrologists and watershed managers and initial investigative studies were begun. Because of positive results produced by the initial investigators, an earth resources satellite called LANDSAT-1 (formerly termed ERTS-1) was launched on 23 July 1972 followed by the launch of LANDSAT-2 on 22 January 1975. The data from these two experimental satellites, the Nimbus reasearch satellite series and the operational environmental NOAA satellites, are currently being used in a wide ranging series of investigations by many scientists concerned with water resources. The results of these latest studies with LANDSAT data are well documented by Freden and Mercanti (11) and Freden, Mercanti and Becker (12).

2. CURRENTLY AVAILABLE REMOTE SENSING SYSTEMS

Remote sensing in earth science is not new and existed prior to 1960 through the employment of aerial photography. Low and medium altitude aircraft have been used for snow surveys, soil mapping, highway location, oil and mineral surveys and land use planning. Although these efforts existed prior to 1960, it appears that the launching of LANDSAT has served to increase interest in the water resources community for exploring in more detail

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1/ Research Hydrologist, Goddard Space Flight Center National Aeronautics and Space Administration (NASA), Greenbelt, Maryland, U.S.A., 20771. Paper prepared for presentation at the Symposium on Watershed Management, American Society of Civil Engineers, 11-13 August 1975, Logan, Utah.

the applications of remote sensing (10). Various types of remote sensing instruments and platforms are available (some especially tailored for water problems) to water resources investigators, but presently the most widely applicable sensors are the Multispectral Scanner Subsystem (MSS) on LANDSAT and the basic multispectral camera array flown on high altitude aircraft such as the U-2. LANDSAT, providing repetitive, regional hydrologic information from 910 km altitude and the U-2, providing high resolution, small area coverage from about 20 km altitude, tend to complement each other over a wide range of basin size and watershed management activities.

Remote sensing flights from low and medium altitude aircraft can generally be tailored to suit the user and can be contracted for from a variety of private concerns and governmental agencies. High altitude missions are flown frequently by NASA's Earth Resources Aircraft Project (ERAP) in support of various satellite missions and other earth science related research projects. The high altitude remote sensing platforms combine the advantages of satellite sensors and low altitude aircraft by being able to obtain high resolution data over medium size watersheds. The sensor package of ERAP has evolved since 1971 to fulfil a broad spectrum of investigator requirements and needs and, as such, should be applicable to most watershed management needs. The basic camera package currently utilized for most flights is a four camera 70 mm format, multispectral array and a Wild RC-10, 6-inch (152 mm) focal length camera. The four matched 70 mm cameras with 45 mm focal lengths are coupled to provide simultaneous images in discrete portions of the photographic spectrum similar to those images provided by LANDSAT. Each matched set of 70 mm images covers an area about 21 km square (approximate scale 1:445 000) with an average ground resolution of 12 m. The Wild RC-10 is a high quality, calibrated mapping camera using 9½-inch (240 mm) wide film. Each scene from the RC-10 covers an area about 30 km square (approximate scale 1:130 000) with an average ground resolution of 7 m. Colour infrared imagery (0.51 - 0.90 μm) is usually taken with the RC-10 camera. A variety of other longer focal length cameras, in various configurations and electro-optical sensors, are available for special purpose flights as required.

Because of the small and medium area coverage obtainable from aircraft, data availability is somewhat restricted for many potential study areas. Spacecraft provide the advantage of repetitive, regional monitoring of dynamic hydrologic systems over any area of interest, sometimes at reasonably high resolutions. LANDSAT 1 and 2 are identical vehicles with orbital characteristics that bring each satellite over any given point on the earth once every 18 days. Each satellite makes 14 orbits a day, viewing a 185-km wide data swath on the earth's surface each orbit. Southward equator crossing occurs at approximately the same time each day - about 09:42 local solar time. This orbital configuration provides a day-to-day sidelap of the data swaths of 14% at the equator; because of the near-polar orbit, the sidelap increases to more than 80% at high latitudes and thus allows daily coverage for periods as long as 6 days in the polar regions. At the time of this writing both LANDSAT 1 and 2 are operating and the orbital configurations are such that the two satellites effectively provide coverage over any point on the surface once every nine days.

The LANDSAT payload consists of the following elements:

1) Multispectral scanner subsystem (MSS). The MSS scans horizontally along the orbital track in 4 spectral bands: green (0.5 - 0.6 μm), red (0.6 - 0.7 μm) and 2 near-infrared bands (0.7 - 0.8 μm and 0.8 - 1.1 μm). During ground processing, 70-mm image frames of areas 185 km square are produced. The ability of the MSS to resolve objects on the earth's surface varies depending on the geometric characteristics of a given object and its contrast with surrounding features; generally the MSS achieves a spatial resolution capability near 80 m.

2) Return beam vidicon (RBV) television cameras. The RBV cameras view a successive 185- by 185-km areas in 3 different spectral bands: green (0.475 - 0.575 μm), red (0.580 - 0.680 μm) and near-infrared (0.698 - 0.830 μm). This system is currently on standby status on both satellites.

3) Data collection system (DCS). The DCS is not a remote sensing experiment but is rather a communications system. It collects information from some 150 remote, unattended, instrumented ground platforms and then relays the information to NASA ground stations for delivery to the users.

Skylab experiments in 1973-74 provided additional high quality space data for water resources studies. The Skylab Earth Resources Experiment Package (EREP), at a nominal altitude of 435 km, used visible light and near-infrared photography and infrared spectrography, an electromechanical scanner and sensors for microwave surveys. The first manned Skylab mission (SL-2) was from 25 May 1973 to 22 June 1973 and included only 11 earth resources data passes. The second mission (SL-3) from 28 July 1973 to 25 September 1973 increased the earth resources passes to 44 and the third mission (SL-4) from 16 November 1973 to 8 February 1974 had 55 earth resources passes. Over 35 000 frames of imagery were obtained in addition to vast amounts of magnetic tape data.

The EREP sensors of prime interest are the six-band multispectral photographic camera (S-190A) and the earth terrain camera (S-190B). The S-190A spectral band images included the visible and near infrared portions of the spectrum with resolutions ranging from 30 to 79 m and covering areas 163 km square. The S-190B produced high resolution colour black and white, or colour infrared images covering areas 190 km square. Depending on the film used, resolutions ranged from 17 to 30 m. Because of the relatively short data collection period, Skylab was not able to provide the regular repetitive coverage available from LANDSAT but was able to produce the highest resolution earth resources photography from space available to date.

On 15 October 1972 the National Oceanic and Atmospheric Administration's NOAA-2 satellite was launched inaugurating a series of medium resolution environmental satellites. Since then NOAA 3 and 4 have also been placed in orbit. NOAA-2 is in a near-circular, sun-synchronous orbit at a nominal altitude of 1 500 km. It crosses the equator southbound at 08:51 local solar time and provides two views of North America daily, one at about 10:00 and one at about 22:00 (local time). The orbital characteristics of NOAA 3 and 4 are very similar to NOAA-2.

The payload of the NOAA environmental satellites includes a number of sensors, but the one of major interest is the Very High Resolution Radiometer (VHRR). The VHRR is a dual-channel scanning radiometer sensitive to energy in the visible spectrum (0.6 - 0.7 μm) and in the infrared (10.5 - 12.5 μm). The instantaneous field of view is designed to be 0.6 mrad for both channels. Ground resolution is approximately 0.9 km at the subpoint. Although the VHRR is designed primarily for direct readout service, a tape recorder provides a maximum of 8½ minutes of recorded data per orbit.

Table 1 summarizes the characteristics of remote sensing systems and data which are currently available to the water resources community for use in watershed management. The following section describes how some of these data sources have been applied to water resources problems.

Table 1 - Characteristics of Remote Sensor Systems Applicable to and Available for Water Resources Management

Vehicle/Sensor	Spectral Bands (μm)	Area of Coverage (kilometres^2)	Nominal Resolution (metres)	Frequency of Coverage
U-2/Vinten multispectral cameras	0.475 - 0.575 0.580 - 0.680 0.690 - 0.760 0.510 - 0.900	425	12	variable
U-2/Wild camera	0.510 - 0.900	875	7	variable
Skylab/Earth terrain camera	0.4 - 0.7 0.5 - 0.7 0.5 - 0.88	11880	17 - 30	variable
Skylab/ Multispectral photographic camera	0.4 - 0.7 0.5 - 0.6 0.5 - 0.88 0.6 - 0.7 0.7 - 0.8 0.8 - 0.9	26570	30 - 79	variable
LANDSAT/ MSS	0.5 - 0.6 0.6 - 0.7 0.7 - 0.8 0.8 - 1.1	34225	80	Once per 18 days (two satellite system provides coverage every 9 days over U.S.)
NOAA/VHRR	0.6 - 0.7 10.5 - 12.5	sub-continent	900	twice per day

3. RECENT REMOTE SENSING ADVANCES IN WATERSHED MANAGEMENT

3.1 Snow Mapping

The most definite snowpack feature that can be extracted from spacecraft or aircraft is the area of the watershed covered by snow. The extraction of snowcovered area from satellites using visible and near infrared imagery has been tested successfully against low and high altitude aircrafts measurements and thoroughly documented in hand-book form (3). The extraction of other more meaningful snowpack parameters, such as water equivalent and depth, is still in the research stage, although water equivalent values obtained by measuring the snow's attenuation of natural gamma radiation from extremely low altitude aircraft have been very promising (4,16). Such techniques are not nearly operational, however, and it is fortunate that a good correlation has been observed between satellite-observed snowcovered area and snowmelt-derived streamflow (22). Two approaches were used to investigate relations between snow extent and runoff. Initially a large watershed without significant upstream diversions (the Indus River above Attock, Pakistan) was monitored from 1967-72 using low resolution, meteorological satellite data and International Hydrological Decade streamgage records. The average area covered by snow near the beginning of April was related in a simple regression analysis to runoff occurring from 1 April to 30 June. The regression relation shown in Figure 1 was significant at the 99% level.

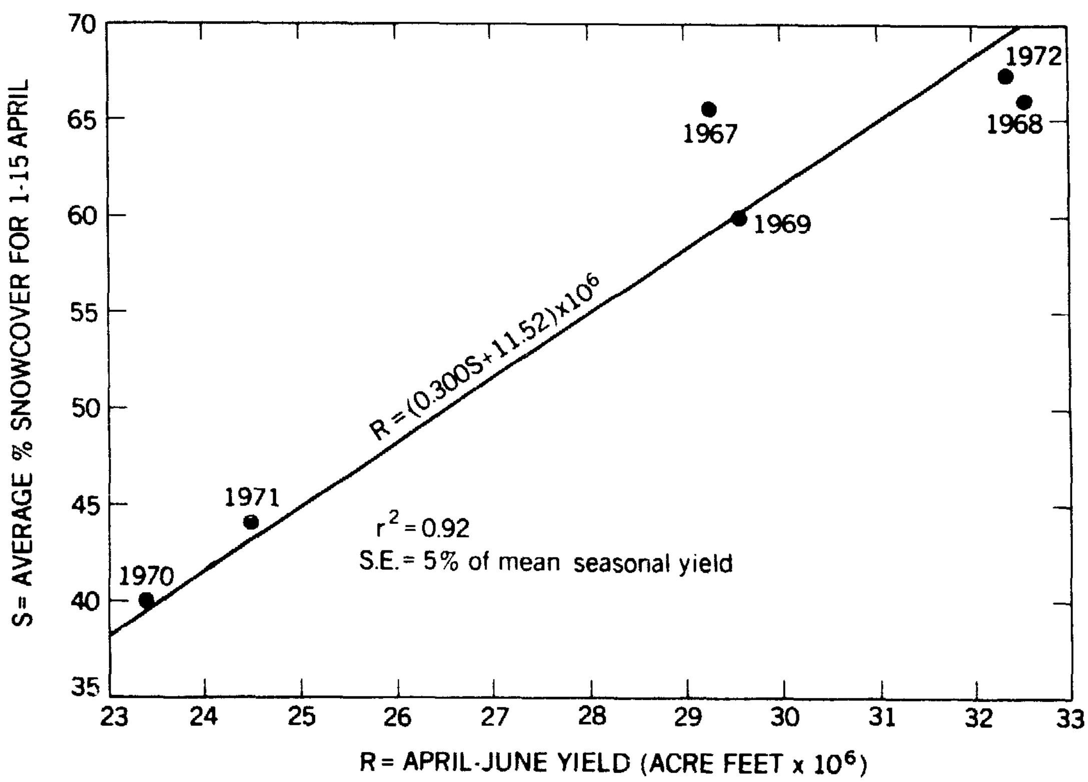


Figure 1. Satellite-Derived Snowcover Estimates Versus Measured Runoff for the Indus River, above Attock, Pakistan, 1967-72.

Subsequent examination of the shorter term, but higher resolution, LANDSAT data in the Wind River Mountains of Wyoming, U.S.A., indicated that similar relationships existed on watersheds as small as 200 km^2. Figure 2 shows the annual variation of snowcover in the Wind River Mountains during the 1972-73 snow season. The snowcovered area was measured in detail on seven small watersheds for two years. Three watersheds were classified as high elevation ($>$ 3 050 m mean elevation) and four watersheds were classified low elevation ($<$ 3 050 m mean elevation). The specific watersheds in these two classes were assumed to be similar for purposes of producing a composite data base with more than two points. The snowcovered area on 15 May was measured and related to the 15 May - 31 July streamflow for each group of watersheds for the two years. Resulting regression relations were also significant at the 99% level. Figure 3 illustrates these relations for the low elevation watersheds.

Although rough estimates of runoff could be made using the equations shown in Figures 1 and 3, the importance of such relations rests in the fact that the differences in the areal snow extent as observed from space are quantitatively related to snowmelt runoff and, as a result, indirectly related to the volume of water on a watershed. Satellite snowcovered area data, in combination with conventionally gathered data, should be most effective as an additional index parameter for seasonal streamflow forecasting and should be useful for reducing errors associated with current prediction techniques. These same snow extent data should be of value to the few watershed models requiring snowcovered area inputs.

6 AOUT 1972

10 DECEMBRE 1972

21 MAI 1973

8 JUIN 1973

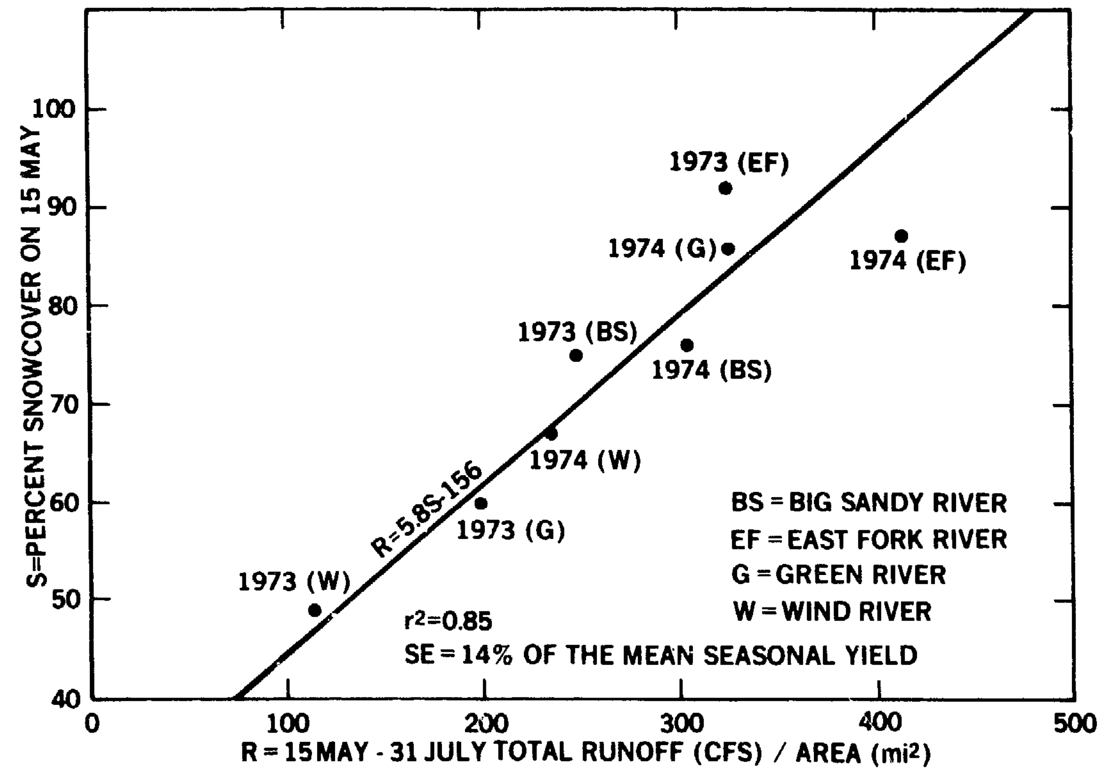


Figure 3. LANDSAT Derived Snowcover Estimates Versus Measured Runoff (1973 and 1974) for Four Watersheds Less than 3 050 metres Mean Elevation in the Wind River Mountains (Rocky Mountain Region), Wyoming, U.S.A.

Because of the promising aspects of satellite snowcover mapping, NASA is currently sponsoring a cooperative demonstration project dealing with the operational applications of satellite snowcover observations. Federal agencies such as the U.S. Geological Survey, U.S. Bureau of Reclamation, Bonneville Power Administration, U.S. Soil Conservation Service, U.S. Army Corps of Engineers and the National Oceanic and Atmospheric Administration and state agencies such as the California Department of Water Resources, Colorado Division of Water Resources and the Arizona Salt River Project are currently attempting to test the satellite data by incorporating them into their operational procedures. This project includes four major study areas and 17 watersheds in the West. The studies underway are employing hydrologic modelling, regression analysis, low altitude aircraft flights, calculation of melting snow areas and the LANDSAT data collection system in addition to basic photo interpretation. Results and cost/benefit analyses from this project will be fully documented.

3.2 Surface Water Inventories

High resolution, near infrared sensors such as those on LANDSAT can be used to definitely measure the extent of surface water because of the strong near infrared contact between water and adjacent land. Numerous results from LANDSAT studies indicate that water bodies as small as 0.01 km^2 can be delineated with ease. This makes the monitoring of surface water using LANDSAT feasible, even on small, inaccessible watersheds. The U.S. Army Corps of Engineers has been employing LANDSAT data for locating and counting bodies of water larger than 0.02 km^2, calculating their area, identifying their shape and locating dam sites on major rivers in response to Federal legal requirements (17). For larger water bodies LANDSAT has also proven useful. Goddard Space Flight Center has recently supplied the U.S. National Committee for the International Hydrological Decade with a computer printout noting the location, surface water area and north-south and east-west maximum dimensions of the 128 surface water bodies in the U.S. that cover more than 100 km^2 as measured from LANDSAT. These data will be used as part of a global surface water inventory. One drawback of using LANDSAT is that for lakes less than 10 km^2 the data reduction and processing becomes formidable for large area surface water inventories.

3.3 Flood Assessment and Floodplain Mapping

LANDSAT data are the most pertinent kinds of satellite information for flood observations because of the relatively high resolution, cartographic fidelity and the near infrared sensors. Mapping of floods using LANDSAT data has been reported by Hallberg, Hoyer and Rango (13), Deutsch and Ruggles (9), Rango and Salomonson (19) and Williamson (29). Areas inundated are detected in the near infrared LANDSAT bands as areas of reduced reflectivity due to standing water, excessive soil moisture and vegetation moisture stress. Most important is the fact that LANDSAT observations, as late as two weeks after the flood crest, will still show the characteristic reduced near infrared reflectivity of the previously inundated areas, which essentially reduces the need for obtaining satellite observations at the time of peak flooding. Other investigations (6,20) have shown that areas likely to be flooded, known as floodprone areas, tend to have multispectral signatures which are at times different than the signatures of surrounding non-floodprone areas. The floodprone areas have unique natural vegetation and soil characteristics as well as different cultural features acquired over a long period of time in response to increased flooding frequency that enable them to be distinguished from the non-floodprone areas. The same investigations cited above have also shown that the LANDSAT floodprone area signatures have, as yet, an unexplained correlation with the 100 year flood engineering and legal boundaries. The reasons for these fortuitous correlations are currently being investigated using LANDSAT digital data.

Flood and floodprone area observations from LANDSAT are indeed promising, but only on a regional basis. Most satellite photographic flood mapping has been done at 1:250 000 scale. Digital LANDSAT flood and floodprone area maps have been produced at 1:24 000 and 1:62 500 scales, but they do not meet national map accuracy standards. For many legal requirements, it is necessary to generate products at even larger scales. As a result flood assessment on small watersheds must generally be done using high resolution, colour infrared photography such as available from the U-2. Such imagery provides the needed resolution for mapping inundated areas. The detection of floodprone areas at required legal scales has also been performed using aircraft data (14). It appears that for most watershed management flooding applications, high resolution aerial photography is the basic and necessary tool. LANDSAT data can be used to provide an excellent regional flooding overview (and on large watersheds) as well as a temporal floodplain monitoring capability. Until higher resolution satellite data are available, however, aircraft will provide the most meaningful data.

3.4 Hydrologic Land Use Analysis

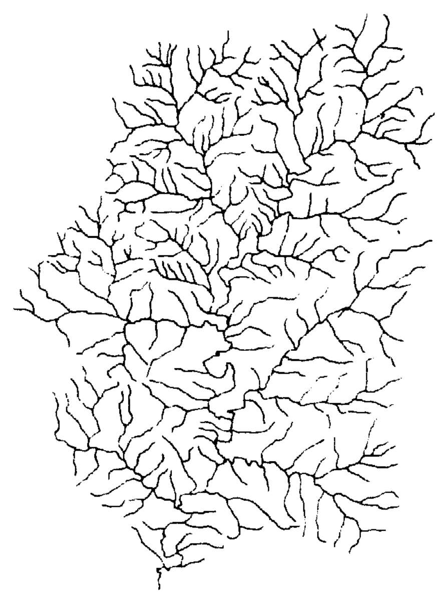
Knowledge of watershed land use is important because a record of surface cover characteristics can be used to refine estimates of the quantity, quality and timing of water yield in response to a particular precipitation event or watershed treatment. Various watershed models require up-to-date land use inputs for calibration purposes and, hence, better streamflow simulations. These land use requirements can be met by various levels of remote sensing data. It is generally agreed that valuable land use maps can be produced from LANDSAT data at 1:62 500 and 1:24 000 scales (2,18). Extraction of such data from LANDSAT information is being carried out at Goddard Space Flight Center using digital multispectral classifications on the Patuxent River watershed. The data from this study have been used to calibrate a parametric hydrologic model on a particular subwatershed 80 km^2 in area. Results from this study indicate a number of weaknesses in data extraction capabilities. First, LANDSAT data from one date alone cannot be used to classify land use of the entire watershed. Temporal data must be used to produce a total area land use classification. Secondly, using satellite data level I (forest land as an example) and only some

Level II (deciduous forest as an example) land use classes can be obtained because of resolution limitations. If more detailed land use information is desired, the high altit U-2 data must be used. Results indicate that all information desired by a planning agenc could be supplied by this data source. Data extraction is much more difficult and expensive from aircraft, however, because it is not as easy to acquire and not as amenabl to automatic extraction as satellite data are. U-2 colour infrared photography over the Patuxent River watershed, however, has been digitized and used in automatic classificatio programmes in the same way as LANDSAT data. Results are similar to LANDSAT, but more detailed.

3.5 Physiographic Characterization

Physiographic observations such as basin area and shape, stream network organizati drainage density and pattern and specific channel characteristics can enable an investigat to estimate the mean annual discharge and mean annual flood flows from a watershed, as we as the rapidity of watershed response to a particular rainfall event. In general, the ki of dynamic hydrologic information available from the repetitive coverage of LANDSAT canno be obtained from topographic maps. Further, in some areas single LANDSAT images offer mo geomorphic information than is available on comparable scale maps (28). In a study cover a variety of U.S. physiographic regions, Rango, Foster and Salomonson (21) found that wat shed area, watershed shape and channel sinuosity measurements from LANDSAT are generally comparable to similar physiographic measurements derived from topographic maps regardless of study area. Drainage networks are well delineated in areas of dissected topography wi detail on 1:100 000 scale LANDSAT enlargements commensurate with information on 1:62 500 scale topographic maps (see Figure 4). Low order streams are difficult to detect in heavily vegetated areas with little local relief or in areas where stream channel develop ment is limited. In such areas LANDSAT derived drainage densities tend to be less than those obtained from equivalent scale topographic maps. Temporal LANDSAT analysis slightl improves physiographic detail in these areas, however, marked improvements in feature dis crimination are obtained only by using high altitude U-2 photography. The combination of these two remote sensing platforms allows for the extraction of all physiographic paramet necessary for a watershed analysis, except for detailed channel dimensions.

LANDSAT 1:100,000 SCALE ENLARGE-
MENT OVERLAY, JANUARY 2, 1973



USGS 1: 62,500 SCALE TOPOGRAPHIC MAP
OVERLAY

Figure 4. The Drainage Network of the Kickapoo River (above La Farge) Extracted from LANDSAT Imagery and U.S. Geological Survey Maps.

3.6 Watershed Models

Much of the information capable of being extracted with the remote sensing approaches mentioned previously can be used in the calibration or operation of numerical watershed models, especially in data sparse regions. The suitable data include land use classifications, stream channel and other physiographic parameters and snowcovered area. The question that must be answered is whether the necessary data can be extracted with remote sensing at the appropriate scale or accuracy. One parameter required of most models is watershed impervious area. This parameter consists of a combination of specific land uses including urban development, streets, parking lots, roof tops and construction sites. The extraction of an integrated percent of impervious area parameter would be exceptionally useful and has been investigated on the Anacostia River watershed in Maryland by Ragan (unpublished results, 1975). LANDSAT automatic classifications of impervious area were compared to results from an earlier study which employed manual measurements taken off low altitude, large scale aerial photographs. Approximately 94-man days were required to complete the required land use analysis using the aerial photographs. Less than three man days were required to accomplish similar tasks using the LANDSAT data. Analysis of the LANDSAT data provided an estimate of the basin imperviousness of 19% whereas the aerial photographic study had resulted in a 24% figure. Agreement between the conventional photographic method and the LANDSAT approach was excellent for subwatershed areas as small as 1.48 km^2. Ragan (unpublished results, 1975) felt that the correspondence between the two methods was more than adequate for any of the hydrologic model impervious area input requirements.

In addition to this study, a sensitivity analysis has been performed which has identified the input parameters in the Kentucky Watershed Model that are amenable to current remote sensing systems (1). The input parameters that can be obtained with remote sensing at an acceptable accuracy include watershed area, fraction of impervious area, water surface fraction of the basin, vegetation interception maximum rate, mean overland flow surface length, overland flow roughness coefficient and fraction of the watershed in forest. Other parameters have been identified as potentially extractable as improvements in image interpretation and analysis techniques become available and new remote sensing methods are developed. Tests are currently being conducted using existing map data and up-to-date information from remote sensing to determine if remote sensing-based model calibrations provide any better streamflow simulations than calibrations based on conventional data. Numerous models, watersheds and kinds of remote sensing data are being evaluated at Goddard Space Flight Center to come up with some definitive conclusions regarding the applicability of remote sensing for watershed modelling.

3.7 Data Collection System

The collection of certain hydrologic information, such as river stage, snow water equivalent, water quality and groundwater level is not presently amenable to operational remote sensing. Nevertheless, accurate and rapid observations of these parameters are needed and satellites provide a dependable means of collecting and relaying this information. The LANDSAT data collection system (DCS) has demonstrated the use of this capability in several instances (7). Some 150 data collection platforms (DCP) are in operation across the United States. At these DCP's, conventional hydrologic measurements are made and relayed via the satellite to the user in near-real time. In Arizona, for example, during the unusually large snowmelt events that occurred during the spring of 1973, data from the LANDSAT DCP's provided essential snowmelt-runoff information in time periods of less than one hour. This hydrologic information considerably improved the management of water runoff in the Salt and Verde River watersheds and lessened the inconvenience due to flooding in the Phoenix area. In general, the reliability of the DCS has been demonstrated to be comparable or better than ground-based microwave telemetry relay systems in all cases tested. The Geostationary Operational Environmental Satellite (GOES) provides an additional data collection system that permits continuous 24-hour interrogation of sensors over large areas. Recent research has seen more attempts to integrate the DCS data and the satellite images in order to more completely characterize the basin hydrologic cycle.

4. DEVELOPING FUTURE REMOTE SENSING CAPABILITIES

4.1 Soil Moisture Determinations

Although soil moisture is one of the most important parameters needed for solving water balance equations for watersheds, remote sensing techniques for assessing soil moisture are currently being developed and have yet to be fully tested. LANDSAT multispectral observations seem to enable relative estimates of soil moisture based on the differential response of wet and dry soils, which is most pronounced toward the near infrared LANDSAT bands. Additionally, multispectral soil mapping with LANDSAT data has been effective in certain areas, generally where vegetation is sparse. In these sparsely vegetated areas, variations in reflectivity appear to be related to moisture in the near-surface soil. The fact that only qualitative inferences about surface soil moisture can be made in bare soil areas does not allow LANDSAT to be used effectively for moisture balance determinations.

The use of thermal infrared data to detect soil moisture variations has been considered based on experiments in Arizona (15). These experiments indicated that the greater the soil moisture percentage by weight, the less the diurnal surface temperature variation. If these initial variations hold true in future studies, thermal infrared data from the VHRR on the NOAA satellites (and other sensors) should be useful in detecting quantitative soil moisture variations that would be useful in irrigation planning. The effect of vegetation is largely an unknown factor, however, and must be evaluated by further research efforts.

Passive and active microwave frequencies are very interesting for soil moisture monitoring because microwave radiation penetration capabilities reveal some information about the make-up of the subsurface. Since the dielectric constant of water at microwave frequencies is quite large (as much as 80), whereas that of dry soil is typically less than 5, the water content of a soil can greatly affect its dielectric properties (24). Recent experiments with airborne microwave radiometers flying over unvegetated terrain indicate that microwave brightness temperature is a function of the wavelength of the radiometer and the distribution of moisture in the soil. It appears that the longer the microwave wavelength, the greater the soil penetrability and the greater the information about soil moisture with depth. Even the shorter microwave wavelengths produce much valuable near surface soil moisture data. In general, the greater the soil moisture percentage by weight, the less the microwave brightness temperature. Soil properties have a much greater influence on the microwave return at short wavelengths (1.5 cm) than at long wavelengths (21 cm). Studies are continuing on the effects of vegetation and surface roughness on the microwave emission from the soil (24).

In December 1972, NASA launched the Nimbus 5 satellite carrying on board the electrically scanning microwave radiometer (ESMR). This coarse-resolution passive microwave instrument (λ = 1.55 cm) provides a capability for monitoring surface and near-surface moisture features over extremely large areas. In an initial study using early ESMR data over the Mississippi Valley, the microwave brightness temperature fluctuations were compared with a number of known hydrologic parameters. The correlations were best with precipitation, indicating that ESMR is indeed monitoring soil moisture changes in a layer just beneath the surface (25). Such observations may provide an index of the susceptibility of a particular area to flooding or its readiness for the application of irrigation water. Watershed studies will not benefit from such information, however, until markedly improved resolution sensors are available. Active microwave experiments show additional promise, but research in this area is only beginning and definite results are not yet available.

4.2 Future Space Systems

A number of satellites are currently in operation and a number of new vehicles will be launched in the next ten years. Varying frequency of coverage and spatial resolution capabilities permit different types of water resources phenomena to be observed with the various systems. Figure 5, adapted from Salomonson (23), shows a representation of various phenomena to be observed, time periods of observation, distance scales and capabilities of existing or planned unmanned spacecraft systems. As an example, LANDSAT generally observes various water resources phenomena no more than once every 18 days and identifies objects with at least one dimension 80 metres or greater. The other currently operating satellites, the Nimbus and NOAA series, are making observations once every 12 hours with resolutions as good as 0.9 km. Note in Figure 5 that many of the applications discussed in this paper are indicated in the areas covered by LANDSAT, Nimbus and NOAA. The Skylab EREP sensors, when operating, had capabilities for irregular time interval observations with resolutions down to 17 m (earth Terrain Camera). A possible follow-up to the LANDSAT satellites will commence with the launching of the Earth Observatory Satellite (EOS) series presently being considered for the late 1970's. EOS would have much the same sampling frequency and types of sensors as LANDSAT, but the spatial resolution capability would increase to 10 metres over small study areas. Beyond the EOS programme, starting sometime after 1980, is a series of Synchronous Earth Observation Satellites (SEOS) which will be able to make observations every few minutes, if desired, at about 100 metre resolutions. Observations from synchronous altitude will be possible by placing a very large telescope ahead of presently available remote sensors. These rapid observations will make possible a better remote sensing characterization of dynamic hydrologic events.

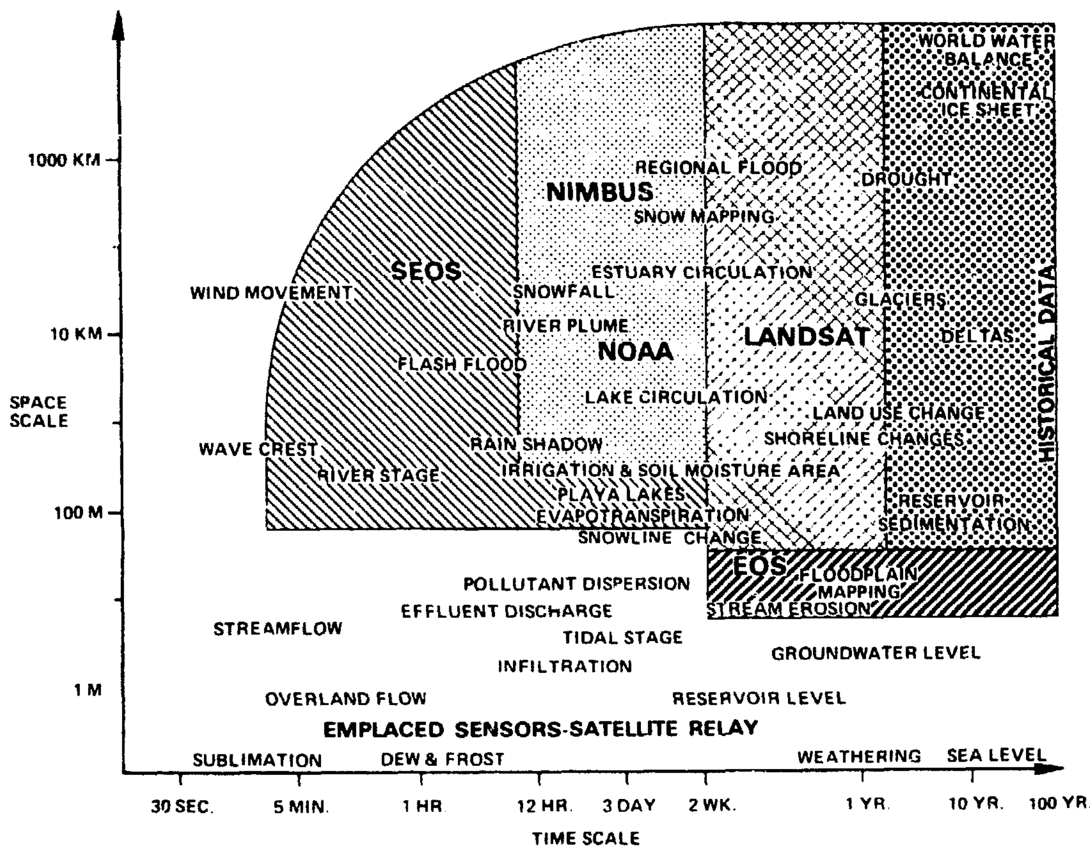


Figure 5. A Time Versus Space Scale Diagram Indicating the Observing Capabilities of Existing and Planned Spacecraft Systems.

The applications and satellites listed in Figure 5 refer only to sensors currently available and not to the development of new or refined instruments. Certainly other portions of the electromagnetic spectrum will be exploited in following years. The Skylab EREP programme with its many varied sensors was an excellent start in the direction of evaluating the advantages of observations in various regions of the spectrum not commonly used. The ERAP programme is also contributing a great amount of information leading to the development and flying of new instruments. Microwave applications will probably be in the forefront of research efforts extending into the 1980's.

Future remote sensing systems will most likely consist of the above satellites with various sensors coupled with satellite data collection systems to rapidly make available conventional hydrologic data. Complimenting this will be data acquisition missions conducted with high, medium and low altitude aircraft and limited ground based surveys. In order to make sense out of this large amount of water resources data, sophisticated, rapid and flexible automatic data processing systems have to be developed to disperse the pertinent hydrologic information to the operational agencies.

4.3 Familiarization With Remote Sensing-Watershed Management Capabilities

In cases where a watershed manager may feel that a particular remote sensing technique may be able to provide him with a desired answer, a lack of knowledge of how to use the data or even where to obtain it prohibits the use of remote sensing. Some ways are suggested here to enable the potential user to become familiar with remote sensing techniques. First, several handbooks or compilations of scientific papers specifically pertinent to water resources exist that would provide a good background for certain water resources applications. The American Water Resources Association has published the proceedings of a symposium on Remote Sensing and Water Resources Management that provides a broad spectrum of the applications of both airborne and satellite acquired data to water quantity and quality monitoring (27). As a result of the fact that snowcover extent mapping has produced a number of positive results, an excellent manual entitled Handbook of Techniques for Satellite Snow Mapping (3) has been compiled. This snow handbook emphasizes the use of NOAA and LANDSAT, but also provides a complete description of other possible satellite snow data sources. The U.S. Army Corps of Engineers has produced a number of documents outlining the applications of remote sensing to water resources that are quite useful. The Cold Regions Research and Engineering Laboratory in Hanover, New Hampshire, has documented the methods to use for locating reservoirs with surface water extent greater than 0.02 km^2 (17). The Hydrologic Engineering Center in Davis, California has published a report on remote sensing applications in hydrologic engineering (5). The third Corps of Engineers document is a manual on remote sensing practice and potential put out by the Waterways Experiment Station in Vicksburg, Mississippi (30).

In order to use LANDSAT (ERTS) data most efficiently, it may be helpful to obtain The ERTS Data User's Handbook (8). These may be obtained for a nominal fee from the General Electric-ERTS Liaison Office in Beltsville, Maryland.

Once a basic knowledge of remote sensing capabilities is acquired, probably the best way to specifically become acquainted with advantages of remote sensing for a particular watershed problem is to obtain some data over the area of interest. These data can then be perused and compared to previous knowledge and conventionally available data to develop a familiarity with the potential uses. The primary place to order remote sensing data is The Earth Resources Observations Systems (EROS) Data Center of The U.S. Geological Survey in Sioux Falls, South Dakota. LANDSAT, Skylab EREP, and high altitude ERAP data can be obtained from EROS at cost by the user. Area to be covered, permissable cloud cover and type of imagery is the only information necessary for ordering. In the case of LANDSAT data, complete catalogues of acquired imagery are also available from EROS at a nominal charge. A catalogue of Skylab earth resources data has also been published by NASA that facilitates ordering of EREP data (26). LANDSAT data may also be ordered from the National Oceanic and Atmospheric Administration's (NOAA) Earth Resources Data Center at Suitland, Maryland, and from the U.S. Department of Agriculture, Agricultural Stabilization and

Conservation Service, Western Aerial Photo Laboratory in Salt Lake City, Utah. NOAA-VHRR data can be obtained from The National Environmental Satellite Service, Visible Products Support Branch in Suitland, Maryland. Information on Nimbus data availability can be obtained from the NASA National Space Science Data Center, Greenbelt, Maryland.

The EROS Data Center, in addition to distributing remote sensing imagery, provides the user with data interpretation assistance through consultation with specialists. Specialized remote sensing equipment is available for users at EROS, as well as several formal workshops and remote sensing training courses. Other remote sensing courses are offered by various Universities with remote sensing specialists on their faculty. For situations where the remote sensing solution to a particular user problem has not been previously demonstrated or documented and the solution is not routinely available from facilities such as EROS, NASA's Goddard Space Flight Center in Greenbelt, Maryland is currently establishing an Information Transfer Laboratory (INTRALAB). INTRALAB will serve to transfer the most recently developed remote sensing technology directly to specific user application problems. It is hoped that the results of the studies performed in INTRALAB will benefit not only the user but also provide NASA with significant input for planning future sensor and data processing systems.

5. CONCLUSIONS

Today's aircraft and satellite remote sensing systems (operational and experimental) are capable of contributing greatly to watershed management, primarily in the areas of snow mapping, surface water inventories, flood management, hydrologic land use monitoring and watershed modelling. As the technological advances in remote sensing of hydrological data continue to accelerate, so must the watershed management community expand its awareness of and its training in remote sensing techniques if these new tools are to be put to optimum use.

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VI.
EVALUATION OF EROSION CONDITIONS AND TRENDS

by

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1. INTRODUCTION

1.1 Statement of the Problem

Erosion has many important consequences for human ecology and economics because it can remove productive topsoil, damage roads and fields by gullying and landsliding, cause eutrophication and silting of river channels and reservoirs, and in many other ways cause environmental degradation that can only be stopped with great effort and cost. Yet erosion is a complicated phenomenon; it is the result of many processes, whose mechanics and controls are not well understood. The number of controls and their interactions limit our ability to predict rates of erosion, although we know that the most important controls are climate and vegetation (and therefore land use), soil characteristics, and topography. Qualitative information of this kind, however, is of only limited use for such purposes as calculating the life of a reservoir, for judging the effects of cultivation techniques on soil loss, or for predicting stream sediment loads under various logging practices.

Smith and Wischmeier (45) have developed a Universal Soil-Loss Equation for the prediction of erosion from croplands. This tool is a useful one for commercial agricultural lands in the United States, and perhaps elsewhere. Its applicability to other regions and other forms of rural land use remains to be tested. The same can be said for other prediction methods based upon multivariate statistical analysis (49). The testing and extension of such methods requires an independent field measurement of erosion. In most developing countries at this time there is not sufficient data upon which to base generalizations like the Universal Soil-Loss Equation. For these purposes, we often must still resort to empiricism, and field measurements of erosion rates are needed.2/

This paper describes a range of field techniques for assessing rates of erosion by various processes. The methods are cheap to use by comparison with most other schemes for monitoring environmental change, and land managers would benefit greatly from the information to be gained from such simple hydrologic and geomorphic measurements.

There are two basic approaches to the study of erosion rates. The first is to monitor sediment transport rates past a point in the river channel at the outlet of a drainage basin. Such measurements are relatively easy to make and they integrate the effects of erosion over large or small areas. They suffer, however, from problems of interpretation, and often it is not easy to decide what is going on within the drainage basin from a point measurement at the outlet. This method, however, is probably the most widespread technique used for monitoring erosion conditions and trends. The second approach to the study of erosion involves measuring processes at a number of sampling sites

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2/ Note: Paper by Arnoldus in this publication describes the possibilities with the Universal Soil-Loss Equation.

within a catchment. Such data are much more difficult to collect but have obvious advantages in providing information about the spatial distribution, controls and local effects of the erosion processes within the catchment. With both approaches, information can be obtained on rates of current processes, and on rates during the recent past, as will be explained.

1.2 Controlling Variables and Sampling Problems

Many erosion-measuring programmes have yielded only limited information because insufficient thought was given to the design of the measurement programme and to the quantification of the major controlling variables. It is not the purpose of this paper to consider either of these topics in detail, but it must be stressed that a few "spot" measurements of erosion can be misleading if they are unrepresentative. The earth scientist must ensure that his measurements sample the range of conditions and the major controlling variables in which he is interested. The problem of sampling is dealt with at an introductory level by most textbooks on statistics (e.g., Krumbein and Graybill, 26) and by several advanced texts (e.g., Cochran, 6).

Even well-distributed measurements, however, will allow few generalizations unless the major controlling variables are also measured. If the controls are quantified and related to erosion rates by simple or multivariate statistical techniques (26), the results can be extrapolated and used to predict erosion rates outside the immediate measuring area. The same data can be used for predictions of the effects of certain changes in the controlling variables, a useful tool in land management.

This reference to sampling and to controlling variables is not a plea for massive statistical studies of erosion, based upon the measurement of dozens of potential controlling variables. Given the difficulty of the fieldwork, such studies are usually not feasible, and most of the multivariate statistical analyses that have been made produce results of little value for land management. It is wise, however, to measure the major variables (precipitation, soil, topography, and vegetation cover) for purposes of developing simple, quantitative relations for the prediction of soil erosion.

For some predictions, the measure of a variable may be a simple one. For example, Langbein and Schumm (31) related sediment yields to mean annual precipitation, and Fournier (11) related them to an index of the seasonability of rainfall. Other predictions require more detailed information such as the kinetic energy of rainfall (e.g. Smith and Wischmeier, 45). Hudson (21) has reviewed methods for quantifying precipitation and soil variables. Methods of measuring vegetation density are described in textbooks on quantitative plant ecology (e.g. Grieg-Smith 15), although much remains to be done in refining the measurement of those characteristics of ground cover which are most strongly related to soil erosion. Topography can be measured by simple survey techniques.

1.3 Temporal Fluctuations and Sampling through Time

Erosion rates fluctuate in time. There may be random inter-annual variations, or periods of several years in which sediment mobilization is intense, perhaps because of a run of wet or dry years. Sharp changes of climate, such as the one we have experienced since the early 1960's (30, 53) also appear to have caused major changes of erosion rates in some parts of Africa. In the American Southwest, climatic change has altered erosion rates several times in the recent geologic past (5). Superimposed upon such "natural" fluctuations are trends of accelerated erosion caused by human use of land. Monitoring erosion rates in the present and the recent past should allow us to separate the effects of land use from those of natural climatic fluctuations. In some situations, of course, these two variables are linked, because changes in the character or intensity of land use often occur in response to climatic change. The interaction, however, must still be evaluated. A long-term view of soil erosion and its response to both land use and to natural environmental fluctuations would be valuable in planning land management.

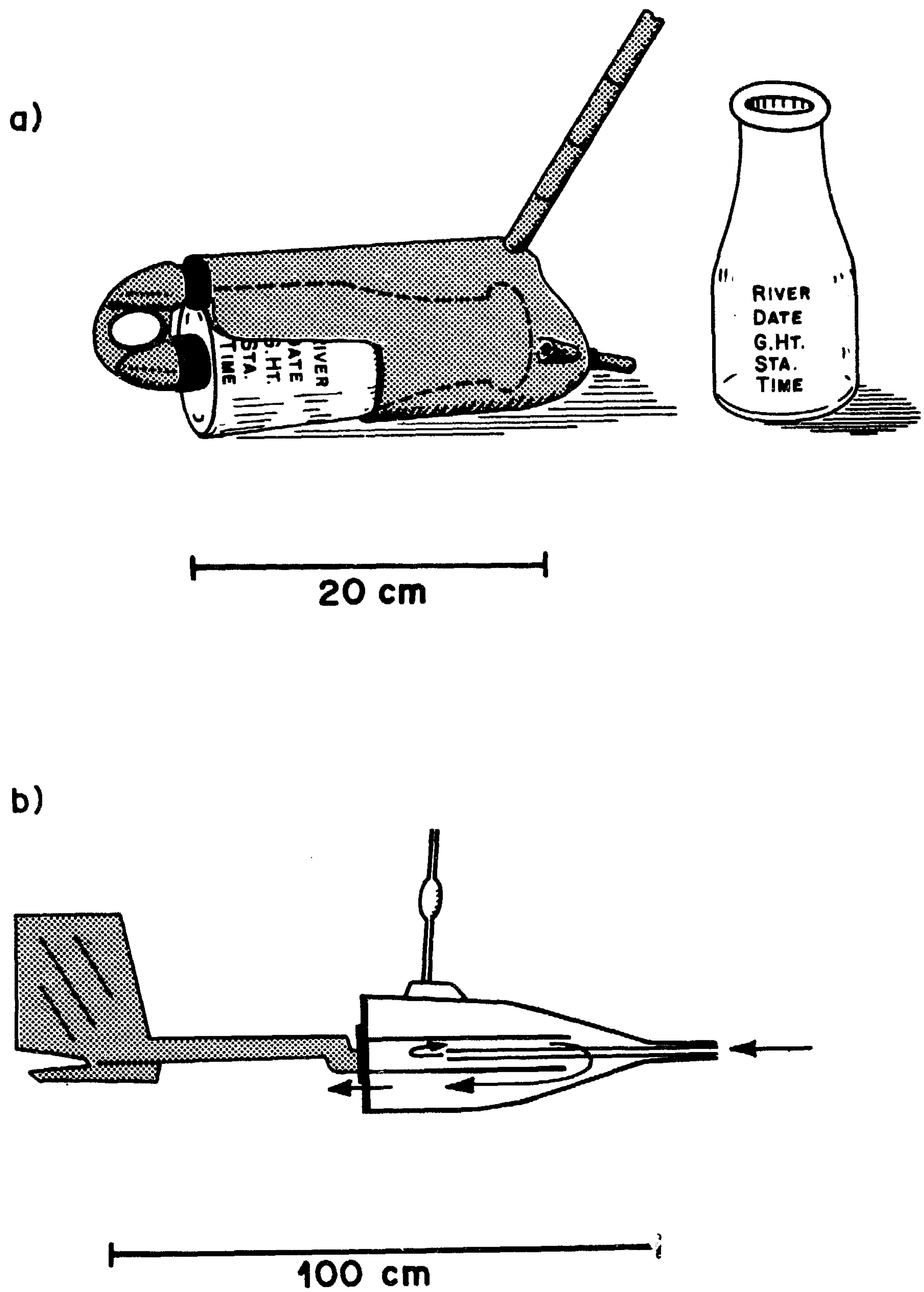


Figure 1. Suspended sediment samplers: (a) USDH-48 depth-integrating samplers; (b) Delft-bottle point-integrating sampler.

2. MEASUREMENT OF EROSION BY SEDIMENT YIELDS FROM BASINS

2.1 Suspended Load

Sediment can leave a basin as suspended load or bed load, and these two components are measured separately. To measure the rate of transport of suspended load, the concentration of sediment in the water is measured (in mg/1) and multiplied by the discharge of the stream (in, say, litres/sec.). Because concentration varies with elevation above the bed a sampling method must be used which provides an average concentration representative of the profile of sediment. The most common instrument for doing this is the depth-integrating sampler (Figure 1a), which allows entry of water through a narrow nozzle into a glass bottle with a capacity of approximately 0.4 litres. Other samplers, (point-integrating samplers) collect only a sample from a particular depth, and allow the vertical profile of sediment concentration to be defined. For details on the use and purchase of these instruments, the reader should consult reports by Guy and Norman (17), and the Federal Inter-agency Sedimentation Project (10). Another widely used sampler, which works on the principle illustrated in Figure 1 (b) is the Delft sampler (38).

Concentration of sediment in the water sample can be obtained by filtration and drying. Kunkle and Comer (27) demonstrated how sediment concentrations can be successfully and rapidly estimated from measurements of turbidity, if a proper correlation is established.

In order to generalize about rates of transport from a few measurements, the suspended sediment concentrations are usually multiplied by the stream discharge at the time of sampling to obtain the rate of suspended sediment transport. This value is then plotted against discharge to yield a suspended sediment rating curve, like that shown in Figure 2a. The curve can then be used in conjunction with a flow-duration curve to calculate suspended sediment yields. The number of days with discharge in some interval is read from the flow duration curve. From the mean discharge for this interval, the sediment transport rate (in tonnes/day) is obtained using Figure 2a. This transport rate is multiplied by the number of days on which it occurred to give the total amount of sediment transported. This process is repeated for each discharge interval on the flow duration curve, and the sediment totals are summed to provide the annual rate of sediment transport. Rating curves of this kind can shift significantly through time (see Figure 2b), as the catchment undergoes fluctuations of climate, land use, or other factors, and once enough measurements have been made to define a rating curve, occasional sampling should be used to check for shifts.

2.2 Bedload

The problem of measuring bedload transport is much more difficult. On small streams with low rates of bedload transport, a trough or catch basin can be installed across the streambed (Figure 3a). The basin can be emptied periodically. This is not feasible in large streams, or where transport rates are high. On a small stream in Oregon, Milhous (36) successfully measured bedload in a trough set obliquely across a channel. The vortex created by the flow of the stream over this trough moved the sediment across the stream to a measuring station installed in the stream bank below the level of the channel floor. In large channels, the rate of bedload transport is measured by lowering a sampling device onto the streambed for a short interval of time. No single sampler has been generally accepted for use, however. The major difficulty lies in the interference of the flow caused by the sampler as it lies on the bed. This can cause either an apparent increase or decrease of the local bedload transport rate. Most samplers also have only a limited collecting efficiency.

Several bedload samplers have been used. Most of them involve some form of wire basket weighted and lowered into the stream on a cable, and stabilized in the flow by a metal tail-fin (Figure 3b). Their catch efficiency is generally low, (often as low as 30-50 percent) because they retard the flow, especially after a small amount of sediment

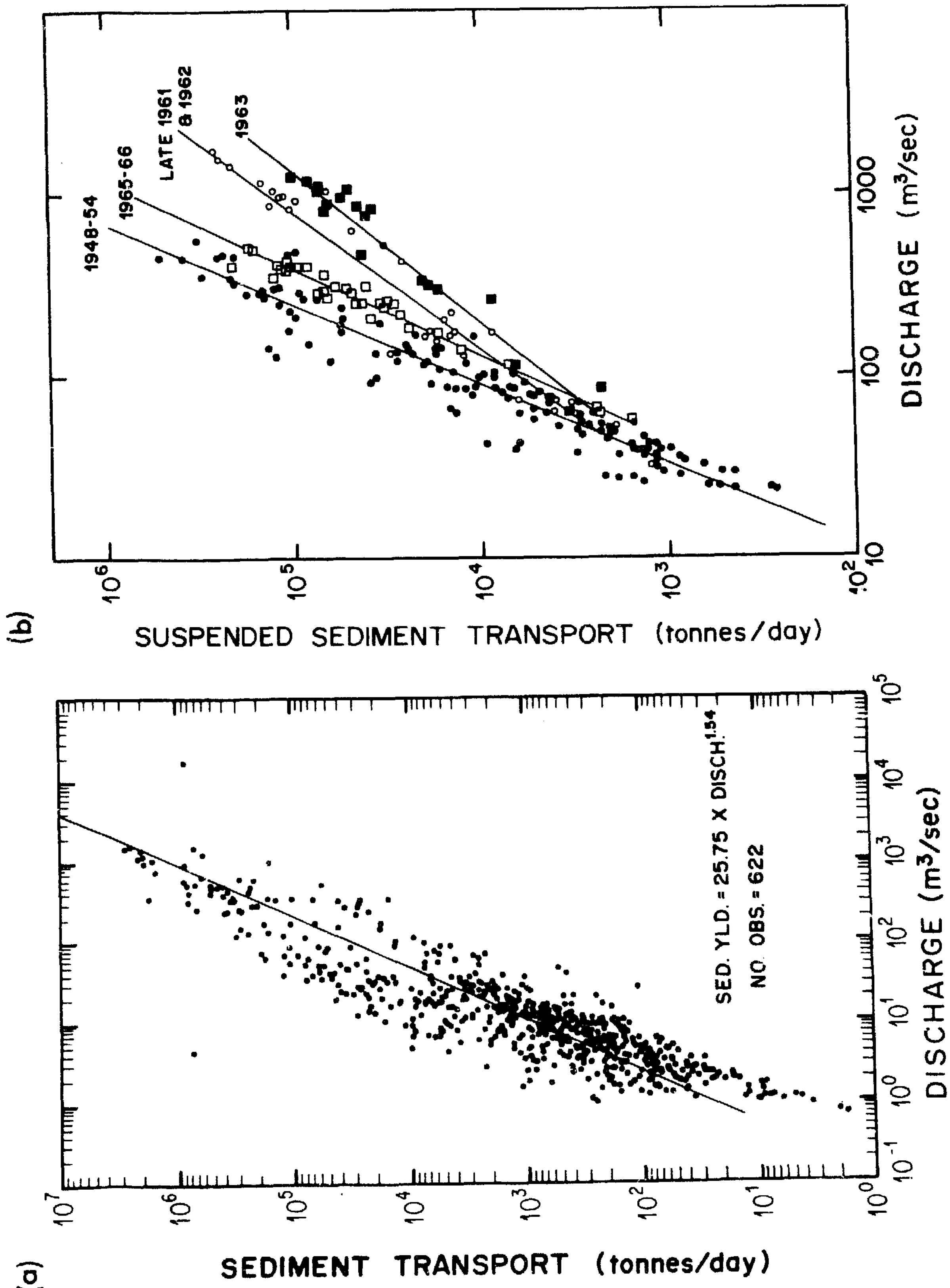


Figure 2. Suspended sediment rating curve for the Uaso Nyiro River at Archers Post, Kenya; (b) Fluctuations of the suspended sediment rating curve of the Tana R. at Garissa, Kenya.

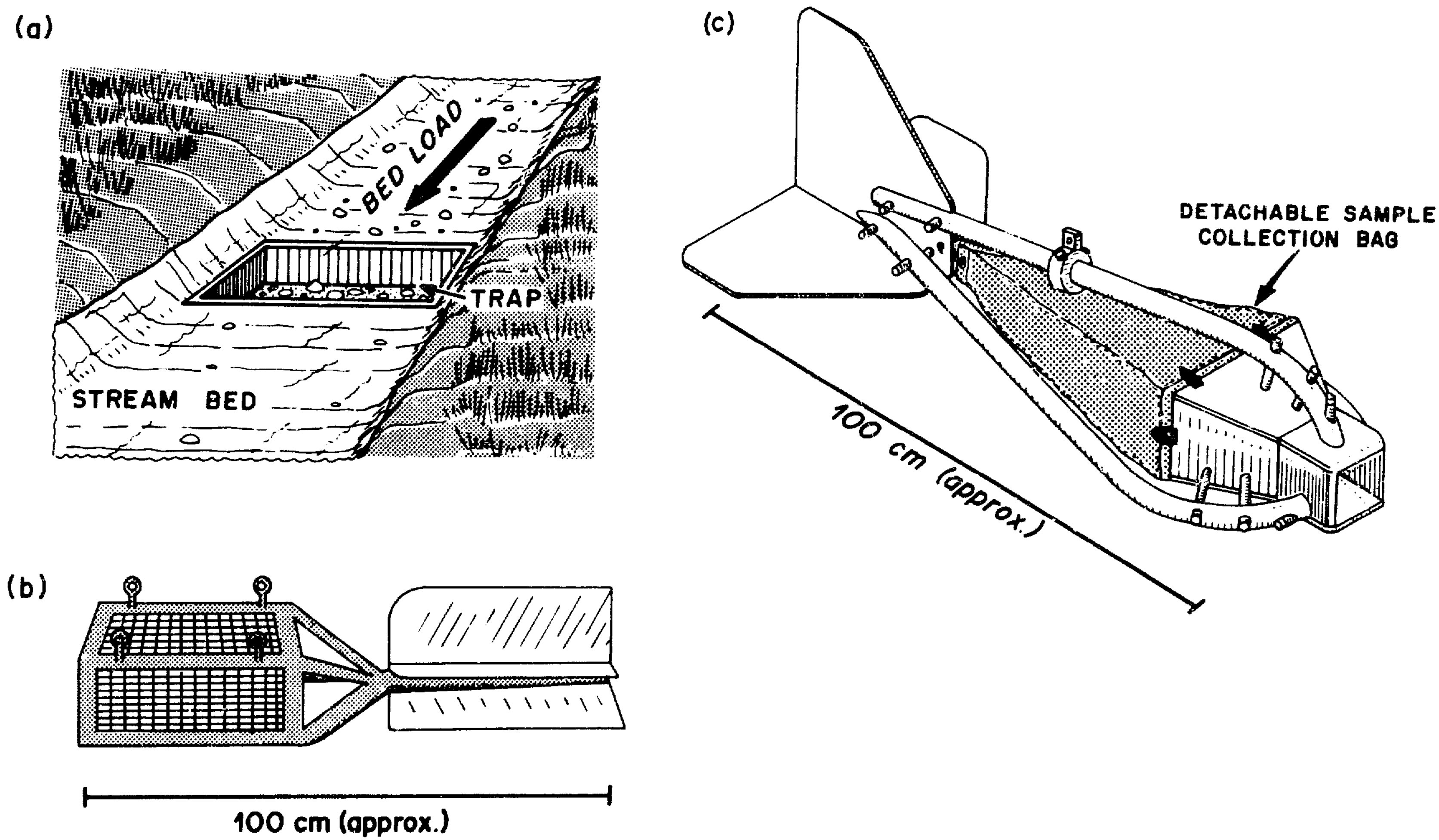


Figure 3. Equipment for measuring bedload transport: (a) a trough installed across the stream bed; (b) a basket sampler; (c) a Helley-Smith pressure-difference sampler.

accumulates within them. To overcome this difficulty, pressure-difference samplers have been designed with a narrow orifice backed by a wider section which causes a pressure drop and allows the flow into the orifice to approximate the ambient stream velocity. This raises the catch efficiency of the sampler. The sediment is caught in a mesh bag, as shown in Figure 3c. One of the earliest successful instruments of this kind was the Dutch Arnhem Sampler, but a more stable and efficient sampler has been designed by Helley and Smith (19). It has a 7.6 cm square orifice, which works very well for material finer than coarse sand. Emmett and Seitz (9) have designed and used one of these samplers with a 15.2 cm square orifice for measuring the rate of transport of gravel. They have also shown by field studies that the 7.6 cm Helley-Smith sampler has a catch efficiency of approximately 100% for particles smaller than fine gravel. As the particle size increases the catch, efficiency decreases. (W.W. Emmett, personal communication, Jan., 1975). Further studies of this sampler are being carried out. The bedload measurements obtained with such a sampler are in units of weight per unit time per unit width of stream. They can be multiplied by the width of the stream to give the transport rate in weight per unit time, and plotted against discharge to produce a bedload rating curve, as shown in Figure 4. Graf (13) presents a useful review of sediment sampling devices.

2.3 Total Load

At some locations the bedload and suspended load are not sampled separately, but the total load for long periods of time can be measured from deposits in natural or artificial lakes, including large reservoirs and small stock ponds. Ideally, the site of an artificial reservoir will have been surveyed before inundation, and if the reservoir is drained periodically the elevation of its bed can be levelled along lines between monumented bench marks. In a lake which is not drained, the changes of bed elevation can be measured periodically by depth sounding from a boat or raft along bench-marked lines. (See paper by Rausch and Heinemann in this publication). Such surveys give only the volume of the deposits, and for purposes such as reservoir design, this may be all that is required. For assessing erosion on the contributing catchment, however, or for comparison with data from sediment transport measurements, the data must be expressed in terms of weight, and this requires estimating the bulk density of the deposits. If local data are available on the density of lake deposits, they should be used. If not, Table 1 will provide useful estimates. Small reservoirs may not trap all of the sediment load of a stream, particularly the finer particles. The proportion of the total load which is caught in the impoundment is called the trap efficiency of the water body and can be estimated from Figure 5. A correction to the total load can then be made for the material that is not trapped. Other methods of estimating trap efficiency for impoundments have been based on particle size of the bed material and sedimentation rates for suspended particles (27).

Table 1: Bulk density of reservoir sediments. Source: Geiger, (12).

Dominant grain size	Permanently submerged (lb/ft^3) 1/	Aerated (lb/ft^3)
Clay	40-60	60-80
Silt	55-75	75-85
Clay-silt mixture	40-65	65-85
Sand-silt mixture	75-95	95-110
Clay-silt-sand mixture	50-80	80-100
Sand	85-100	85-100
Gravel	85-125	85-125
Poorly sorted sand and gravel	95-130	95-130

1/ lb/ft^3 = pounds per cubic foot; multiply the above figures by 16.02 to obtain kg/m^3.

2.4 Sediment Yields

Within a region of uniform climate, geology, and land use, the sediment yields from large drainage basins are usually less than those from small basins, and the latter in turn are less than rates of sediment loss measured on hillslopes by the techniques to be described in the next section. When comparing sediment yields from basins of various sizes, therefore, the yield must be corrected to remove the effect of catchment size. Alternatively if measurements of erosion from hillsides and gullies are being used to assess the probable rate of sedimentation at some proposed reservoir site downstream, the erosion rate must be corrected to express how much of the soil that is mobilized on the hillsides will reach the downstream point. The remainder of the mobilized soil is deposited on gentle footslopes, debris fans, floodplains and other depositional features.

The ratio (expressed as a percentage) of the soil loss from hillsides and gullies to the sediment yield of a catchment is called the sediment delivery ratio of the catchment. This ratio varies with drainage basin size, and with the overall steepness of the catchment. If local data are available, the variation of sediment yield with these factors can be quantified, but if such data are lacking, Figure 6 may be used to estimate the sediment delivery ratio. The degree of scatter in these diagrams, however, should be taken into account when conclusions are being drawn about measurements corrected in this way. A review of the available literature from several physiographic regions indicates that the exponent in the equation relating sediment delivery ration to drainage area generally varies between -0.15 and -0.35, but that values cluster strongly around -0.20 over a wide range of catchment size. When comparing sediment yields from drainage basins, it is usual to correct them all to a value appropriate for a basin of a fixed size.

If reservoir surveys are made periodically, temporal variations in sedimentation rates can be calculated. For estimating sedimentation rates over long periods of time before any survey was made, samples from various depths can be dated radiometrically. Such measurements can be useful for indicating long-term erosion rates, which average out short runs of rapid or slow sedimentation. They can also indicate erosion rates before the advent of large-scale human modification of the land. Stuiver (46) has discussed the application of radiocarbon dating to the measurement of variations of sedimentation rates in lakes over the last 10,000 years. For this method organic materials must be collected from various depths in a sedimentary deposit and transported carefully to a laboratory with the appropriate equipment. Ralph (40) clearly describes the method, the kinds of materials that can be dated, and the collection and packaging of samples. Radiocarbon dating is not useful for materials less than several hundred years old. Sediments ranging in age from 10 to 100 years can be dated by measuring Lead-210, an isotope from the uranium-238 series. This isotope can be used for calculating sedimentation rates over the recent past, which is of most interest to the land manager, and holds great promise for work in sedimentation. The technique is described by Koide et al (23) and by Petit (39). Where radiometric facilities or materials are not available, stratified fluvial deposits can be dated from archaeological evidence (Leopold et al (33) pp. 480-84).

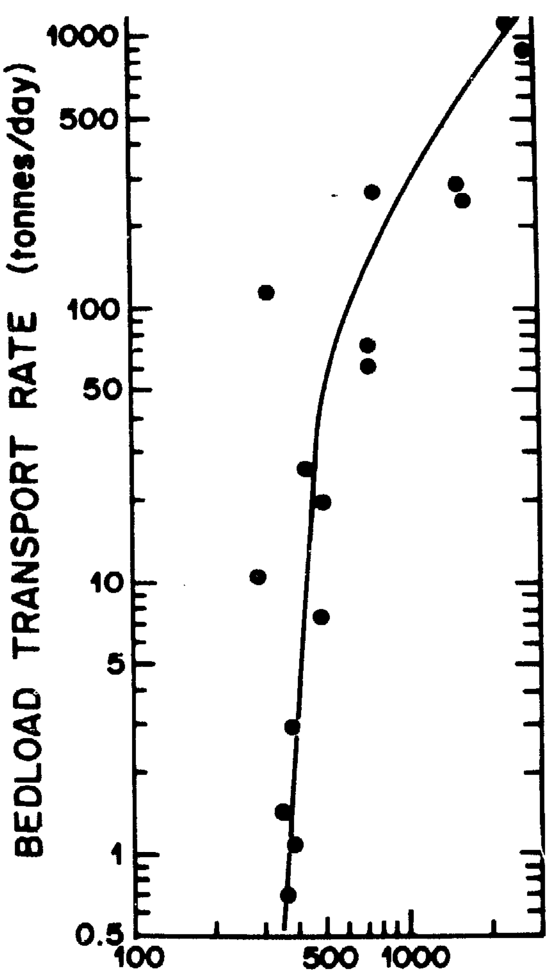


Figure 4. Bedload rating curve, clearwater River at Spalding, Idaho.
(Emmett and Seitz, 1973)

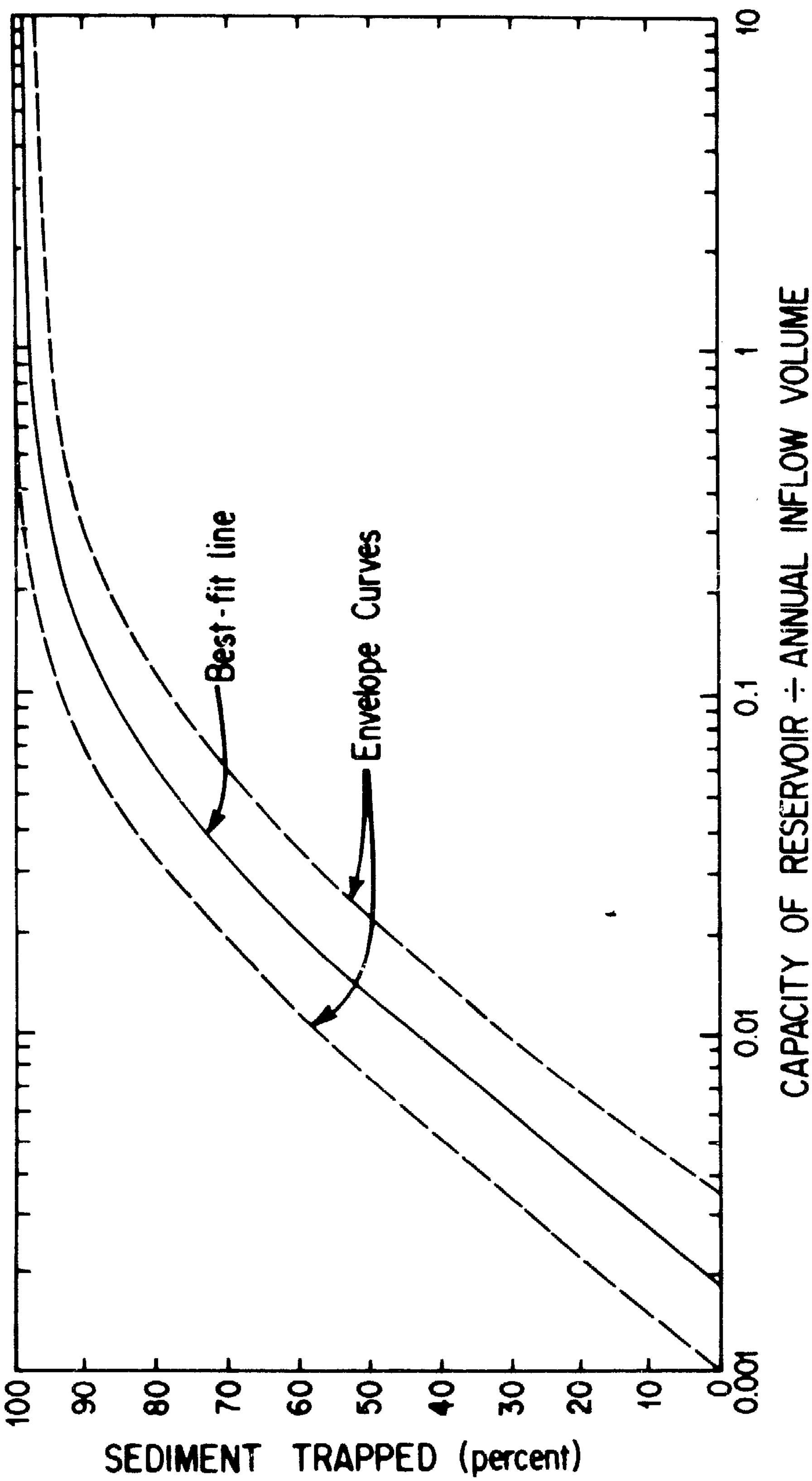
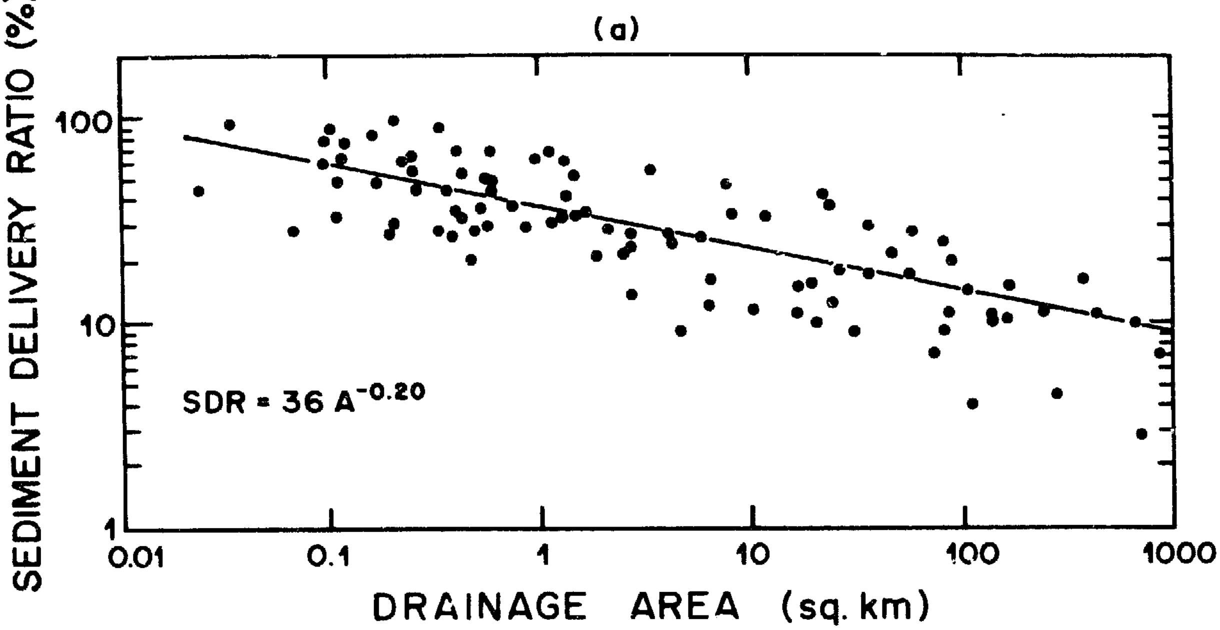


Figure 5. Method for estimating trap efficiency of lakes and reservoirs based on comparison of the reservoir's capacity to the volume of water which flows into the reservoir. Source: Brune (1953).



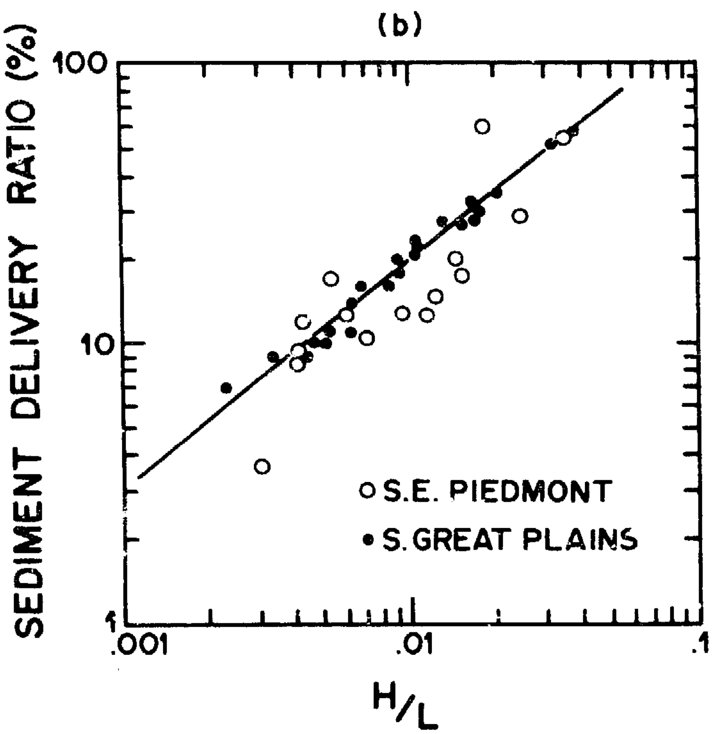


Figure 6. (a) Relation of sediment delivery ratio to catchment size for drainage basins in the central and southeastern United States. Source: Roehl (1962). (b) Relation of sediment delivery ration to catchment relief (H) and mainstream length (L) for drainage basins in the southern United States. Sources: Maner (1958); Roehl (1962).

3. MEASUREMENT OF EROSION WITHIN CATCHMENTS

3.1 Sediment Sources

Sediment yields from drainage basins provide a useful index of erosion conditions and trends. Often, however, the land manager needs more detailed information about where the sediment comes from within a catchment, what the major processes are that mobilize the sediment, and what the relation is between the intensity of erosion and various possible controlling factors. The techniques used for measuring erosion within catchments vary with the erosion processes themselves. The processes to be discussed here include: sheetwash erosion; rilling and gullying; river channel changes; mass movements and wind erosion.

3.2 Sheetwash erosion

3.2.1 Plots

Current sheetwash erosion can be monitored by measuring the amount of sediment washed from hillside plots, or by measuring the rate of lowering of the ground surface at stakes. An erosion plot can be established simply by installing a collecting trough along the contour and connecting it to a tank in which the eroded sediment and runoff can be measured. Also note example given in the paper by Djorovik in this publication. The length of the trough may vary according to the wishes of the investigator. Longer troughs sample a larger section of hillslope, which minimizes errors due to the spatial variability of erosion caused by minor rills. Small plots are often defined by inserting metal or plastic walls a few centimetres into the soil. Such small plots, varying in width from about 0.5 m to 2 m are often used for studying infiltration and soil erosion under controlled artificial rainfall (35). Larger plots are usually left unbounded and are defined approximately by a topographic survey.

The construction of the collector trough is usually simple, but the trough must be carefully installed if it is to function properly. Figure 7 shows some suggested designs. The crucial factor is to provide good contact between the lip of the trough and the soil surface, so that runoff enters the trough satisfactorily and does not erode the lip and by-pass the trough. Gerlack used a small (50 cm long), sheet-metal trough placed in a shallow tranch (Figure 7a). The trough has a hinged lid to prevent the ingress of rainfall, and a 3.5 cm wide lip which is pushed under the soil surface. A drain from one corner of the trough conducts sediment laden runoff to a storage tank. Such a short trough is satisfactory if there is no significant spatial variability across the slope. The ease of construction and installation allows several troughs to be installed en echelon down a hillside to study the effects of hillslope length upon erosion.

If small rills are present, the investigator may wish to use a longer trough. A collector can be constructed, as shown in Figure 7b, by driving stakes into the soil along the slope, and nailing to them 20 cm wide boards. The boards can then be used to support a collector. If the plot is only several feet long and if the cross-sectional profile of the hillslope is smooth, sections of sheet metal can be laid side-by-side and soldered together. Their uphill edge can be inserted into the topsoil as shown. If the hillside is not smooth, however, and if the collector needs to be a long one, thick industrial polyethylene sheet can be used. One edge of the sheet can be fastened to the supporting backboard and the sheet spread down the board and uphill along the ground. A short slit is made about 2 cm into the soil surface, and the edge of the polyethylene sheet is tucked into this slit with a piece of wood. The base of the polyethylene channel can then be covered with a bituminous roofing compound to keep it smooth. It is also advisable to provide for a considerable gradient on such a channel so that it drains the runoff water and sediment efficiently toward the storage tank. A plastic collector of this type is less durable than other materials, but is cheaper and easier to install if long troughs are needed. Inserting a lip under the topsoil works well if the soil has a moderately good vegetative cover, but where the root mat is not strong, the soil tends to disintegrate

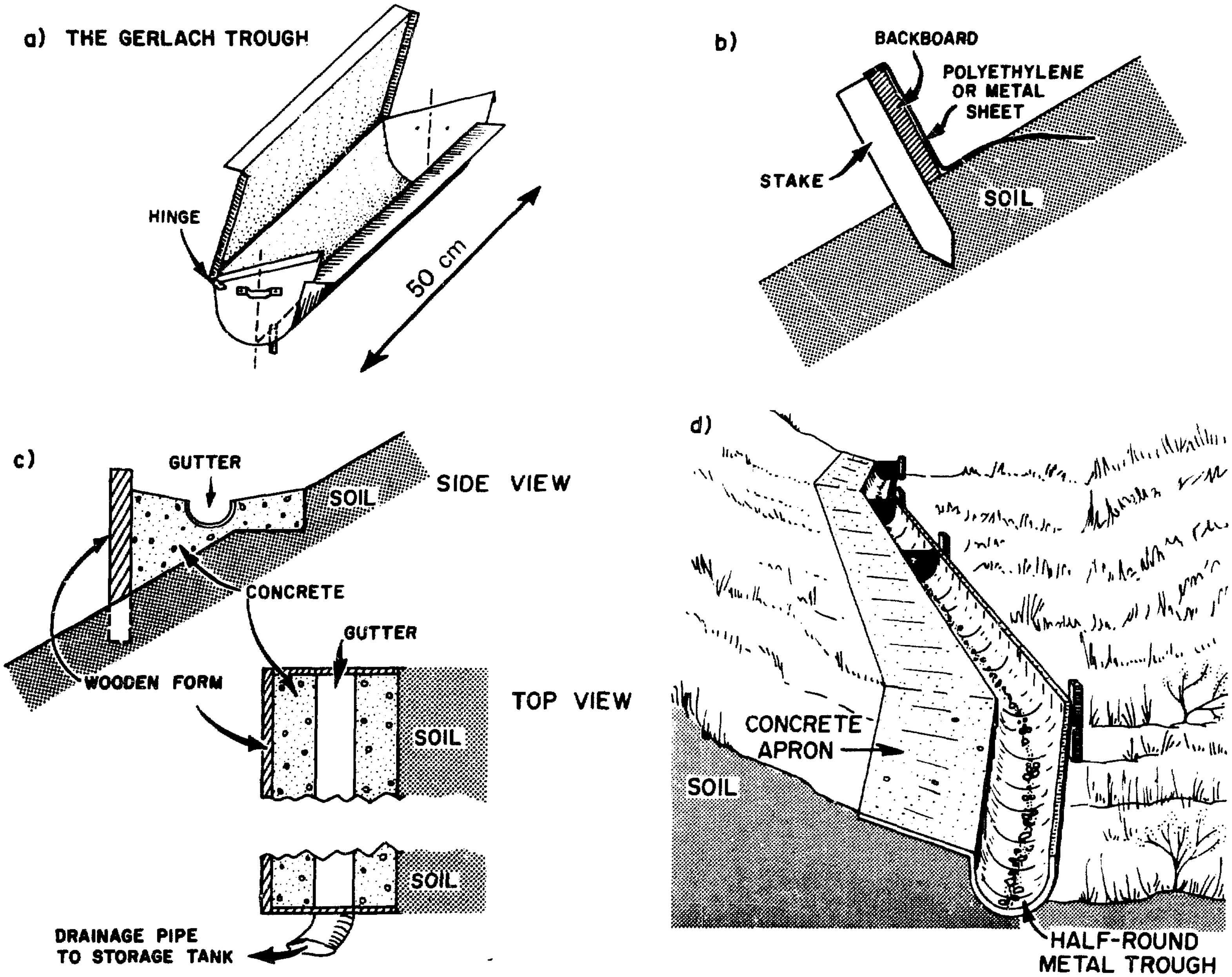


Figure 7. Collector troughs for measuring runoff and soil eroded from hillside plots. (a) Gerlach trough; (b) Channel consisting of a backboard and sheet; (c) concrete gutter; (d) large debris trough.

immediately above the trough. In such cases, it is better to install a concrete trough, as shown in Figure 7c. The width and depth of the concrete channel must vary with the magnitude of flows to be expected from the plot.

Where erosion rates are extremely high and where eroded debris may be very coarse, a larger collecting trough is required. Anderson et al (2) used half-round steel troughs to catch debris from steep hillslopes in Southern California (see Figure 7d). The upslope edge of the trough was connected to the soil surface by a concrete apron, and one-metre high reinforced wooden boards were positioned behind the trough to catch bouncing rocks.

If the plot must be large, the design of the storage tank must take into account the potentially large volumes of sediment and runoff to be collected. One inch of runoff from a hillside plot 200 feet long and 50 feet wide would total 850 cubic feet of water (one foot = 0.30 metre). Rather than construct such a large storage tank, some investigators install devices that divert only a small portion of the runoff and sediment into the measuring tank (37).

3.2.2 Stakes and Pins

An alternative method of measuring sheetwash erosion involves repeated measurement of the height of the ground surface at stakes or erosion pins. The instrumentation shown in Figure 8a consists of a 25 cm long nail and a large washer. At the time of installation, the nail and washer are driven into the soil. The distance from the head of the nail to the top of the washer is then measured with a millimetre scale. Erosion removes material from around and beneath the washer which is lowered to the position shown in Figure 8b. Remeasurement of the distance between the top of the nail and the top of the washer provides a measure of the erosion rate during the intervening period. If the washer has protected the soil from raindrop impact, so that it now stands on a small pedestal, the pedestal must be removed before measurement, so that the washer lies at the general level of the ground surface. The advantage of using the washer is that it gives a firm surface from which to measure. Such monitoring devices are cheap and easy to install in large numbers. A wide range of conditions can therefore be sampled at small cost. The most valuable illustration of the use of such data in understanding erosion processes and their relationship to the sediment budget of a drainage basin is the work of Leopold et al (33).

Marking the pins with bright red paint and placing them in a grid pattern or along a line facilitates relocation. Near each group of pins, should be an easily located bench mark, clearly identified by a numbered tag or engraved plate. The records of installation should include detailed instructions on how to locate the bench mark, and how to locate the groups of pins from the benchmark. The value of these simple measurements lies in their repetition, and the work is wasted if records of the pin locations is lost when the original investigator changes his job. At the time of each erosion-pin survey, the elevation of the top of each pin should be checked by running a line of levels from the bench mark. This will indicate whether the pins have been displaced by frost heaving or trampling.

3.2.3 Other Erosion Indicators

In addition to measuring current rates of soil loss, it is also sometimes possible to reconstruct the recent erosional history of an area from truncations of soil profiles, from the height of residual soil pedestals, or from the exposure of tree roots. A lot of care must be exercised when using these methods, and local undisturbed soils and tree roots must be examined in detail. Normal spatial variations of soil-profile depth with hillslope gradient and other factors, for example, should be considered when using measurements of truncated soil profiles. Haggett (18) measured the combined thickness of the A and B horizons of a soil on the mid-sections of slopes that had been planted to coffee in Brazil. By comparison with similar measurements under nearby undisturbed forest, he was able to show that 20 cm ($\pm$ 5 cm) of soil had been removed from the cultivated slopes since 1850. A comparison of the textures of the two sets of soil profiles confirmed this conclusion.

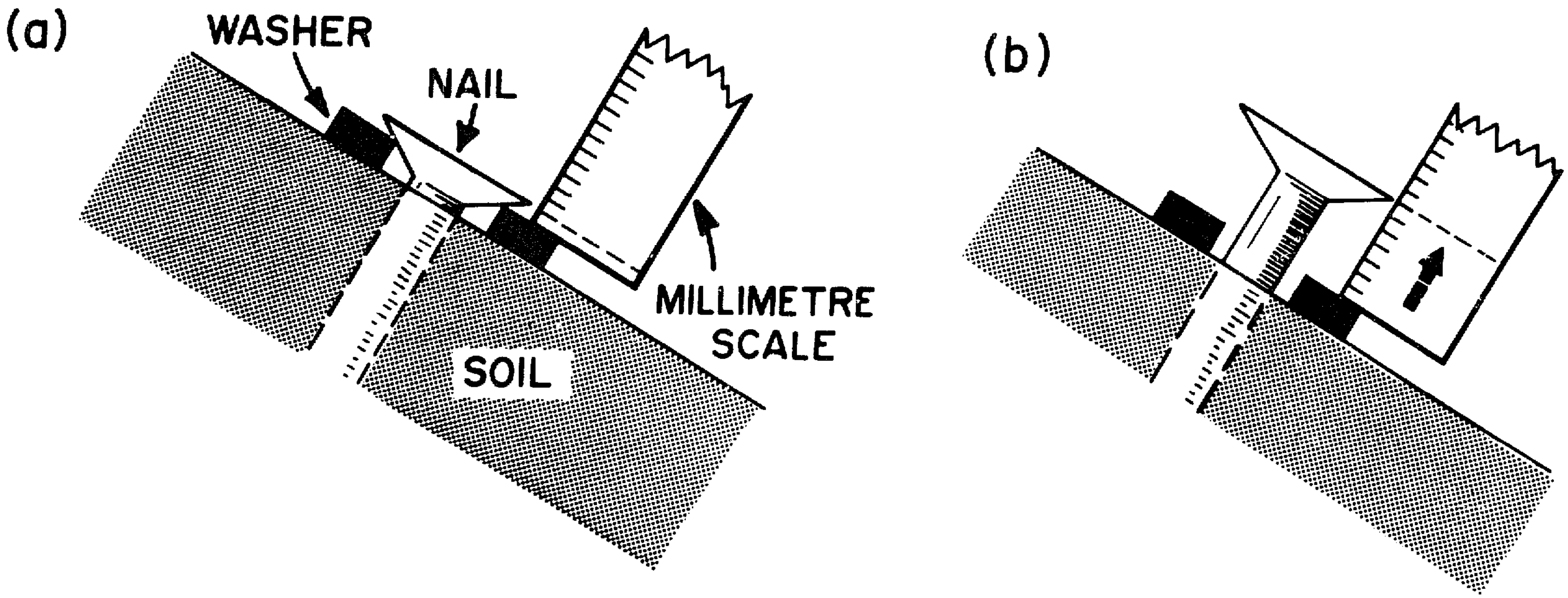


Figure 8. Measurement of erosion and deposition at stakes: (a) Installation; (b) Remeasurement.

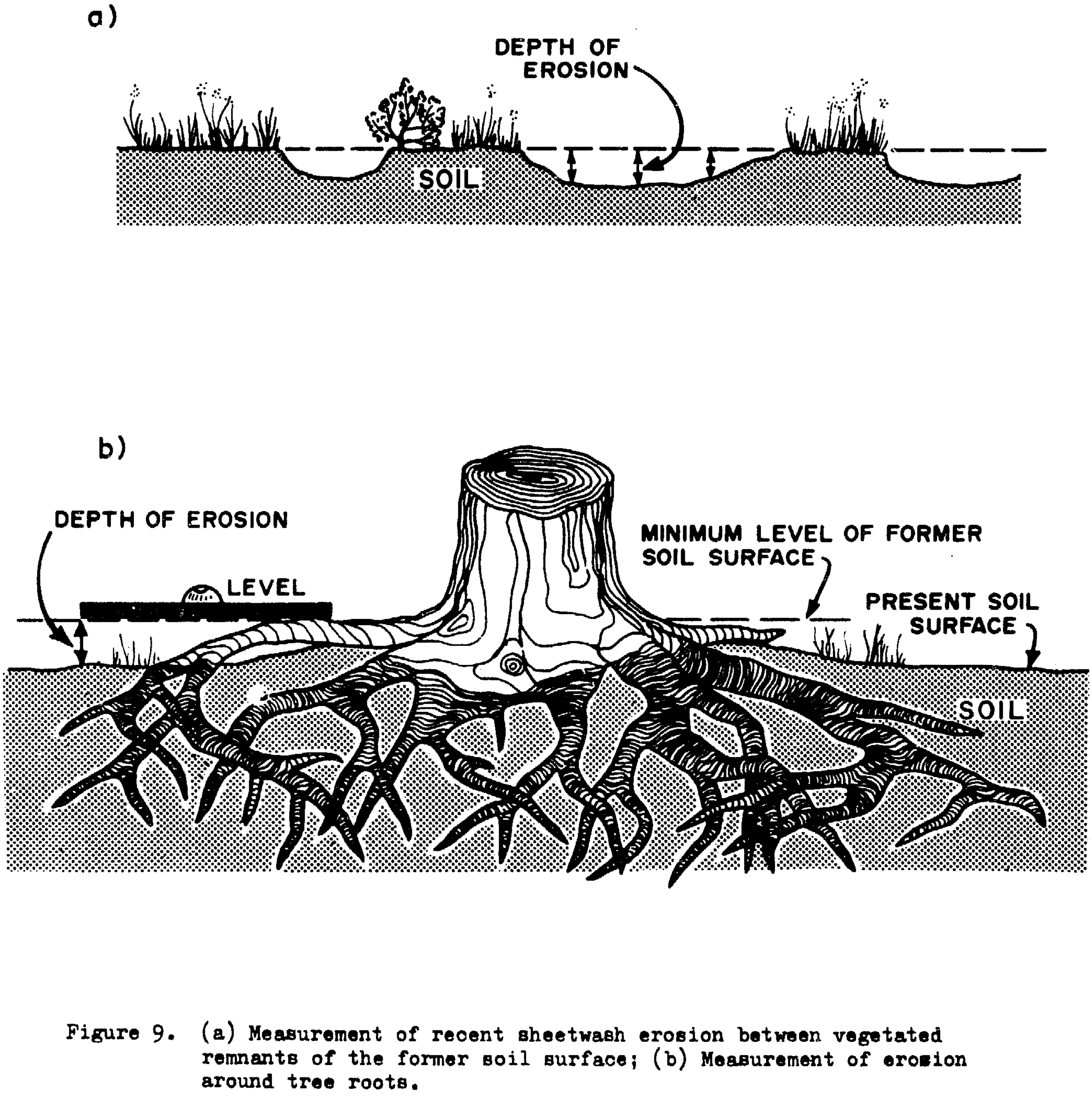
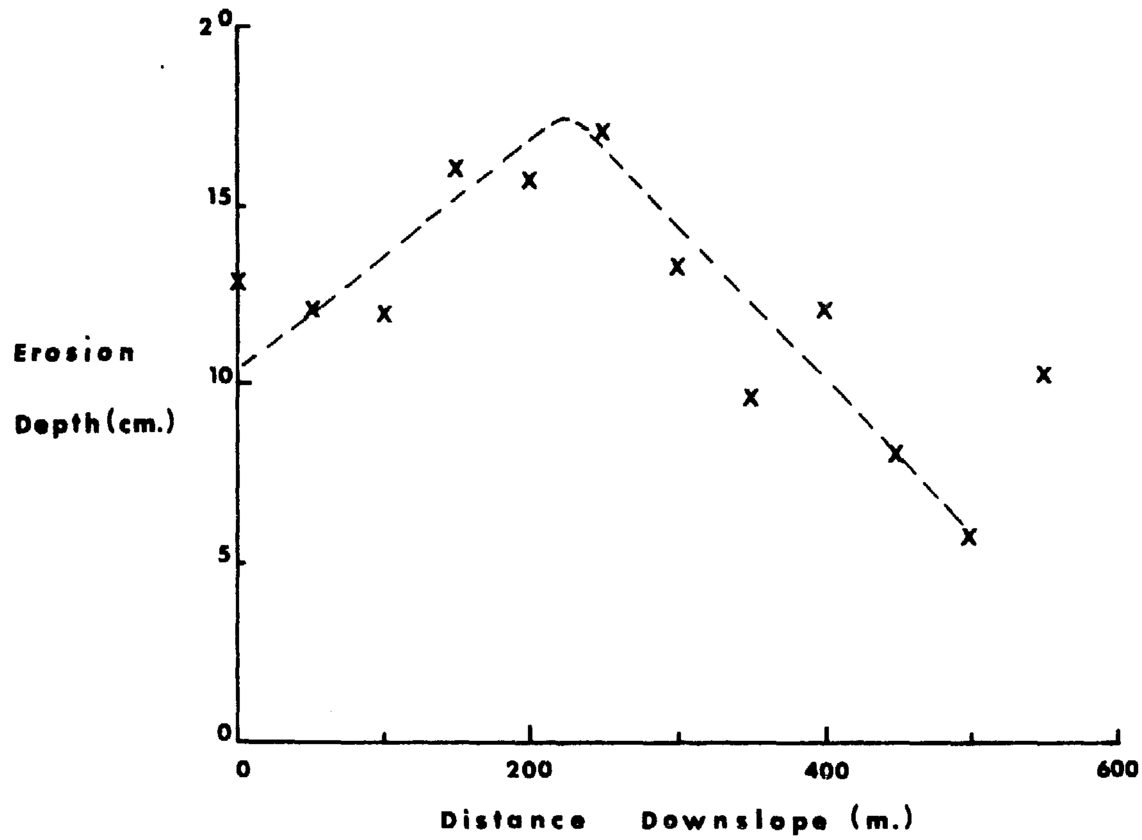


Figure 9. (a) Measurement of recent sheetwash erosion between vegetated remnants of the former soil surface; (b) Measurement of erosion around tree roots.



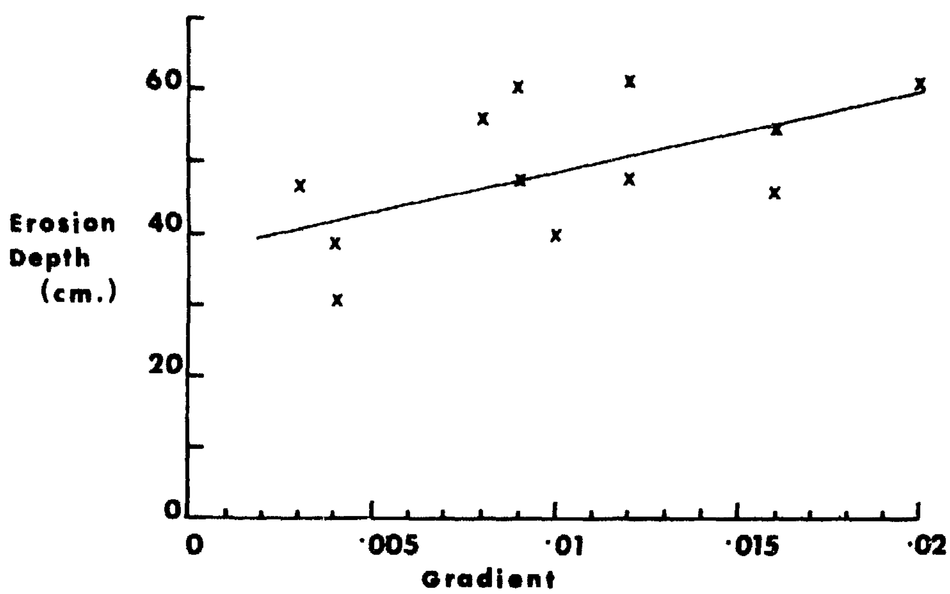


Figure 10. Depths of erosion measured from tree root exposures. Each point represents an average of 5-10 trees within a small area.

Particularly if soil erosion is rapid following the destruction of a vegetative cover, remnants of the former surface may be left, as shown in Figure 9a. A ruler, frame, or tape laid across the former surface can be used as a reference from which to measure the average depth of erosion. Various other indices, such as the average distance between remnants or the average width of remnants along a transect can also provide sensitive information that will indicate changes between repeated surveys of the same area. The exposure of tree roots can be measured, as shown in Figure 9b. Before such measurements are made, the investigator should examine roots of trees from the same species in neighbouring areas. Some trees, even on undisturbed sites, grow with part of their roots above the ground surface. The average depth of the basal flare of the trunk below ground should also be examined at undisturbed sites; in Figure 9b, only a minimum depth of erosion is indicated for a tree species whose roots lie wholly within the soil at undisturbed sites. The methodology and limitations of using tree-root exposures for measuring erosion has been discussed in detail by Lamarche (29). Measurements of root exposures at various sites produces data of the kind shown in Figure 10 and allows the investigator to relate erosion rates to their controlling variables.

A minimum date for the duration of the accelerated erosion can sometimes also be obtained from the age of the tree, which in some climates can be measured by counting the number of annual growth rings on newly-cut stumps, or in cores taken from the living tree with a Swedish increment borer (obtainable from major engineering supply houses). In many tropical regions, however, annual growth rings do not form, and the trees must be aged by some other method such as measurement of their diameter. The relationship between diameter and age can be obtained by measuring annual increments of diameter on a sample to trees. Pedestals can also be dated from the ages of long-lived shrubs which grow on them, but the techniques for aging shrubs are not as well developed as those for trees. If the tree has been cut down, the age of the surface can sometimes be obtained from aerial-photographic evidence of the data of destruction of the woodland, from local records, or from local oral tradition. Rough estimates can be made from the extent of weathering of the wood, or from the nature of the charcoal if the stump has been burnt. All such estimates would be affected by such variables as the climate and the nature of the wood (i.e. the tree species). In making the estimates, therefore, there is no substitute for local field experience.

3.2.4 Classification Approach

In some studies there is not sufficient time or manpower to make detailed measurements of erosion depths. The intensity of erosion is estimated by inspection of large areas, and is mapped onto aerial photographs. This technique usually involves the establishment of three or four catagories of erosion intensity. Areas of perhaps 10-200 acres, or individual hillslopes are then classified into one of these categories (note 1 acre = 0.4 ha). The erosion classes should be well-defined and carefully described. Photographic documentation of type localities will give other investigators, land managers and planners a clear idea of the erosion conditions represented by each category. The classification may vary with the form that erosion takes in a particular region, but it is useful to seek agreement between all the workers surveying erosion in a region. As an example, the classification adopted by the U.S. Soil Conservation Service (48) for classifying water erosion is listed below.

Class 1: Up to 25 percent of the original A horizon, or original ploughed layer in soils with thin A horizons, removed from most of the area.

Class 2: Approximately 25 to 75 percent of the original A horizon or surface soil lost from most of the area.

Class 3: More than 75 percent of the original A horizon or surface soil, and commonly part or all of the B horizon or other underlying layers, lost from most of the area.

Class 4: The land has been deeply eroded until it has an intricate pattern of moderately deep or deep gullies. Soil profiles have been destroyed except in small areas between the gullies.

Because of the association between the density of the vegetative cover and erosion rate, the vegetation can sometimes be used as an indicator of erosion if all other important controls are fairly constant. Thus, the percentage of bare soil, the canopy density, or density of ground cover have all been used as indices. They do not, of course, take into account that for a fixed cover density, erosion will be faster on steeper slopes and more erodible soils. They are, however, easy to measure repeatedly and are generally incorporated into any inventory of range condition. Although the use of erosion indicators is a relatively crude technique it can be used to define quantitatively the conditions of geology, soils, topography climate and land use which retard or accelerate erosion. Measurement of these controlling factors for each site at which erosion conditions are classified allows the investigator to study the association between various degrees of erosion and values of the controlling variables using statistical techniques that are appropriate for ordinal and nominal scale variables (20, 26). (Note also paper by Stevens in this publication).

3.3 Rilling and Gullying

If large gullies have grown or are growing rapidly in a region, their development can be measured on sequences of aerial photographs (3,44). The date of initiation of gullying can also often be established from aerial photographs. Many gully systems, however, can generate large amounts of sediment by only small enlargements of their headcuts or by minor retreat of their sidewalls. The measurement of these processes is not possible from aerial photographs. Even plane-table maps or pace-and-compass maps are not generally accurate enough for this purpose. Changes in gullies, and in smaller features such as rills, should be measured by repeated level-surveys at benchmarked cross-section and along the profile of the gully. Iron stakes driven 20 cm into the ground provide adequate benchmarks for this purpose. Widening, deepening, and the migration of headcuts can be quantified in this way. An example of the results of repeated surveys is shown in figure 11a. Several such cross-sections should be installed along the gully. The average net change at two adjacent cross-sections should be multiplied by the distance between the cross-sections to obtain the net volume of erosion or deposition.

For detailed monitoring of the behaviour of vertical headcuts, an arrangement of stakes, such as that shown in Figure 11b will allow repeated tape measurements to be made. In this way, retreat averaging a few inches per year can be measured with ease. The amount of sediment mobilized by rills can be measured either at lines of erosion pins, or by repeatedly running lines of levels along the contour between benchmarks (see Figure 12).

3.4 River channel changes

Some changes in river channels can be observed from sequences of aerial photographs. Disappearance of riparian vegetation, bank caving, or direct measurements of width and sinuousity may all provide quantitative evidence of net erosion if it is large. On the ground, repeated mapping of river channels onto aerial-photographic mosaics, or by plane-table, chaining, or pace-and-compass mapping can indicate large increases of channel width, sinuousity, or shifts of position. Lateral movement, however, and the presence of raw, undercut banks do not necessarily indicate a net loss of sediment from the valley floor. By repeated levelling of benchmarked cross-sections of a small stream, Leopold et al (33) were able to show that the sediment eroded from the undercut bank was approximately in balance with the amount of sediment deposited on the opposite streambank as the channel shifted laterally (see Figure 13). The deposited material came from the drainage basin or from the valley floor upstream, the net amount of erosion or sediment production within the surveyed reach was approximately zero. If the bank being undercut is higher than the

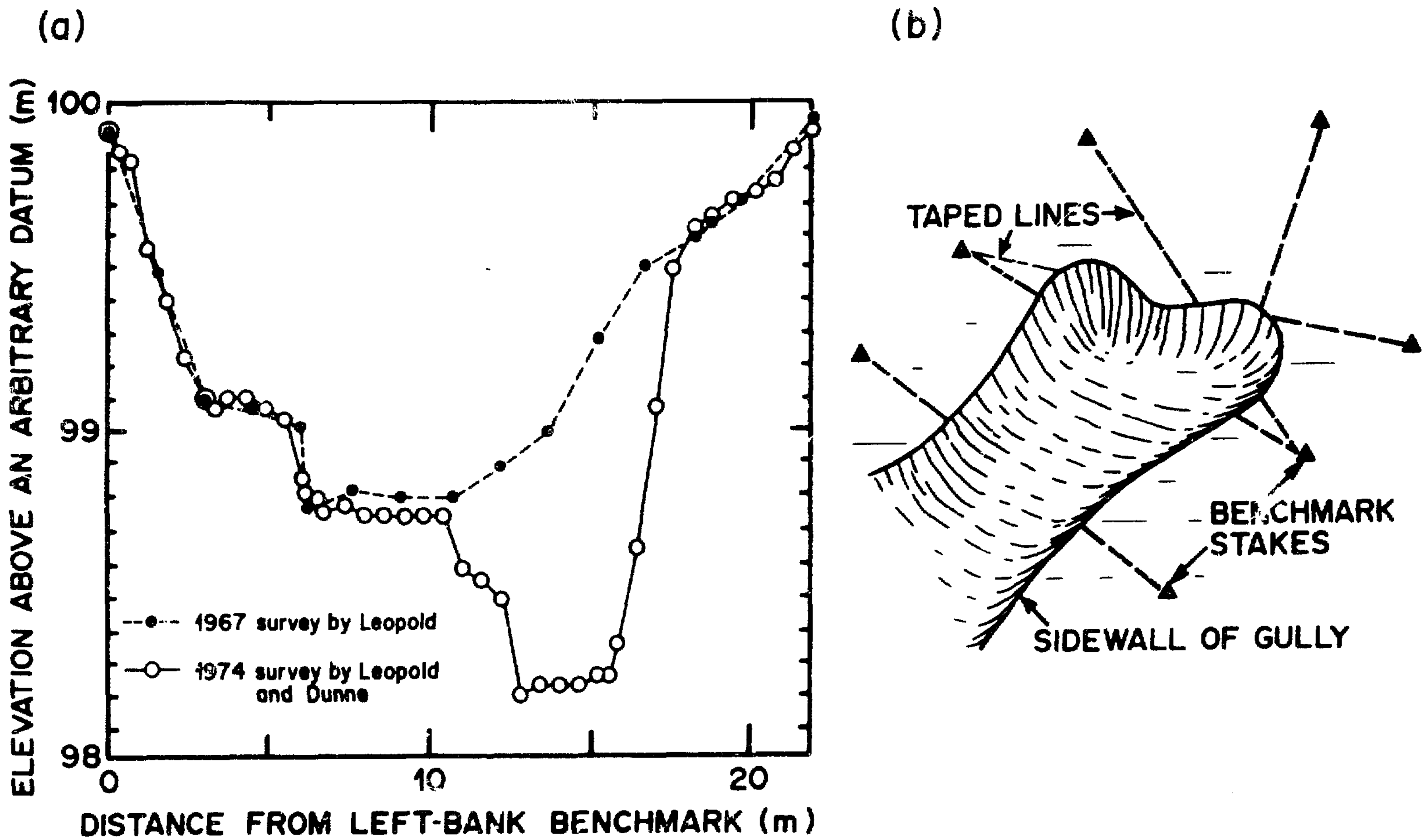


Figure 11. Measurement of gully changes: (a) by a level survey at a bench-marked cross-section; (b) by taping distances from a number of bench marks.

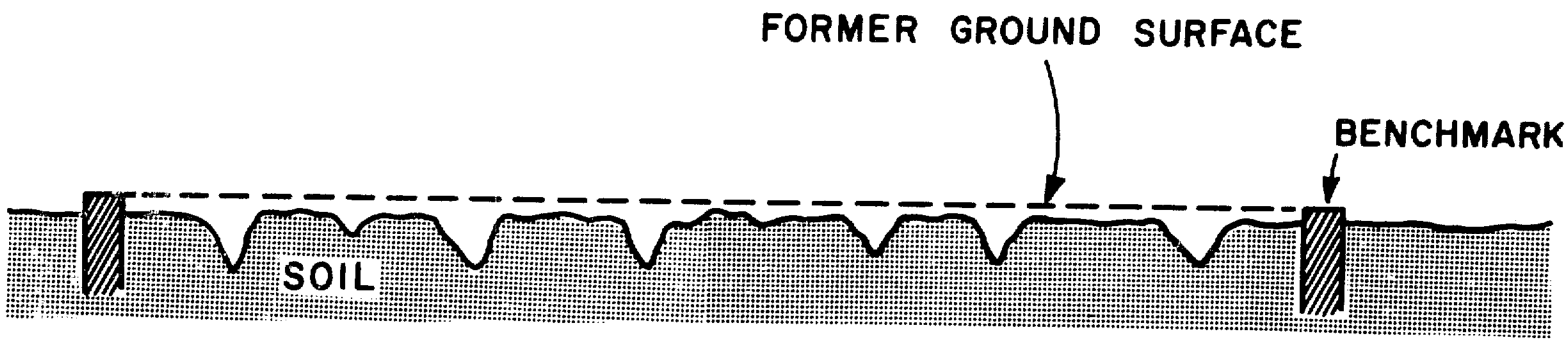
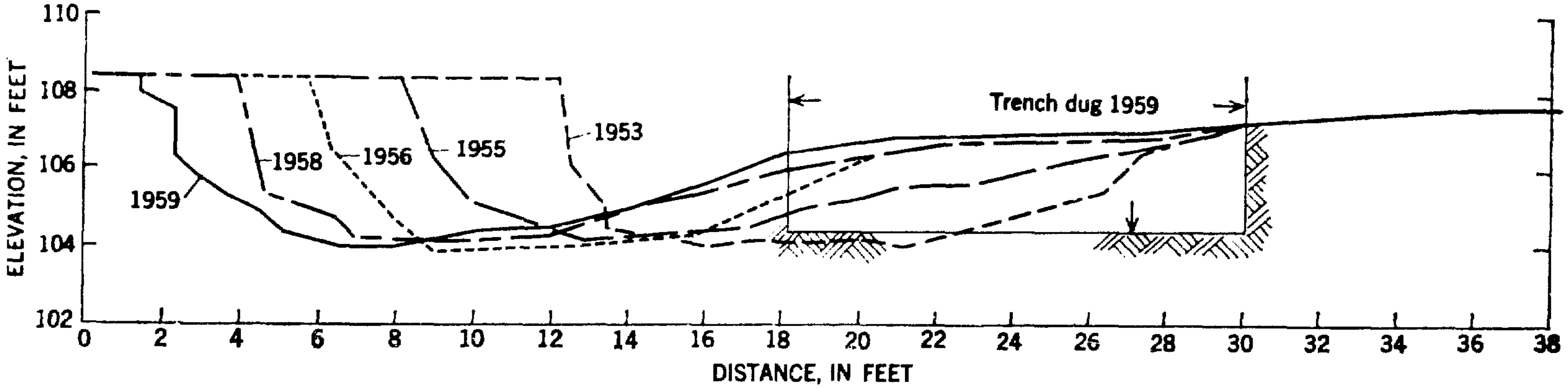


Figure 12. Measurement of rills by levelling along the contour between two bench marks.



Successive surface profiles of meander channel and point bar, 1953-59

Figure 13. Repeated measurements of the channel cross-section of a stream, showing bank erosion and channel shifting without net loss of sediment. Source: Leopold et al (1964).

one being deposited, however, there is a net loss of sediment from the reach. This erosion can best be quantified by establishing several bench-marked cross sections on a stream and multiplying the average net loss of sediment from adjacent cross-sections by the distance between the sections. If bank recession is very rapid, or is highly variable, it can be monitored by repeatedly measuring the distance from the bank to lines of stakes well back from the stream. Grey (14) has provided a detailed description of methods for measuring bank erosion during snowmelt floods.

3.5 Mass movements

3.5.1 The Types of Mass Movements

It is difficult to measure rates and trends of erosion by mass movement because the processes are either very slow or catastrophic. One may be concerned either with their importance as producers of sediment, or as agents of land destruction and hazard. The former aspect is particularly difficult to study, the latter is more tractable. Mass movements can be classified in many ways (see 50), but for the purpose of discussing measurement techniques, I will divide them into: creep, landslides, earthflows and mudflows.

3.5.2 Creep

Creep is the downhill movement of soil and weathered rock due to slow deformation under the downslope component of gravity, and to small downhill movements as the soil is disturbed by frost action, wetting and drying, or the soil fauna. It is generally imperceptible except by careful, precise measurements over a number of years.

The most widely used and accurate method of measuring creep involves the use of a Young pit (Young, 54) as modified by Emmett and Leopold (8). A pit is dug to the depth to which creep penetrates, and a benchmark (iron stake) is driven into the subsoil, as shown in Figure 14. Two other benchmarks are placed in line with the one in the pit, and in the top of each benchmark, a narrow groove is scratched. A theodolite is centred over one of the benchmarks to establish a line of sight approximately along the contour through grooves on the other two benchmarks and through the sidewall of the pit (Figure 14b). A narrow vertical slit is then made into the sidewall of the pit on the line of sight. Into the slit a flexible metal strip is inserted. The strip consists of a number of 2.5 cm x 5 cm aluminium plates, held together by sticky tape (masking tape, or insulating tape), as shown in figure 14c. This tape will eventually be destroyed by weathering, and the plates can move independently of one another. When the strip is installed in the slit, a millimetre rule is held horizontally at the top and bottom corner of each plate. The deviation of each plate from the line of sight can then be observed through the theodolite. The initial position of each plate is thus defined precisely. The pit is carefully refilled and its position relative to some surface marker is carefully measured.

For the re-survey, the pit must be relocated and excavated slowly with a hand trowel, so that the plates are not disturbed. The line of sight is again established with a theodolite set over a bench mark and horizontal deviations from the line of sight are measured with a millimetre scale set on the top and bottom corners of each metal plate. The measurement can be continued by carefully re-filling the pit. Repeated measurements on each plate establishes its average velocity. Multiplication of this value by the depth increment represented by the plate and by the width of the hillslope provides an estimate of the rate of sediment production in cubic metres of soil per year. A simpler but less accurate method of measuring creep has been tested by Rudberg (43) and is useful where creep rates are high.

For very deep soils undergoing rapid creep, Kojan (24) successfully employed long flexible tubes inserted several metres into the soil. Deformation of these tubes are still beingmeasured repeatedly by means of an inclinometer lowered to varying depths inside the tubes.

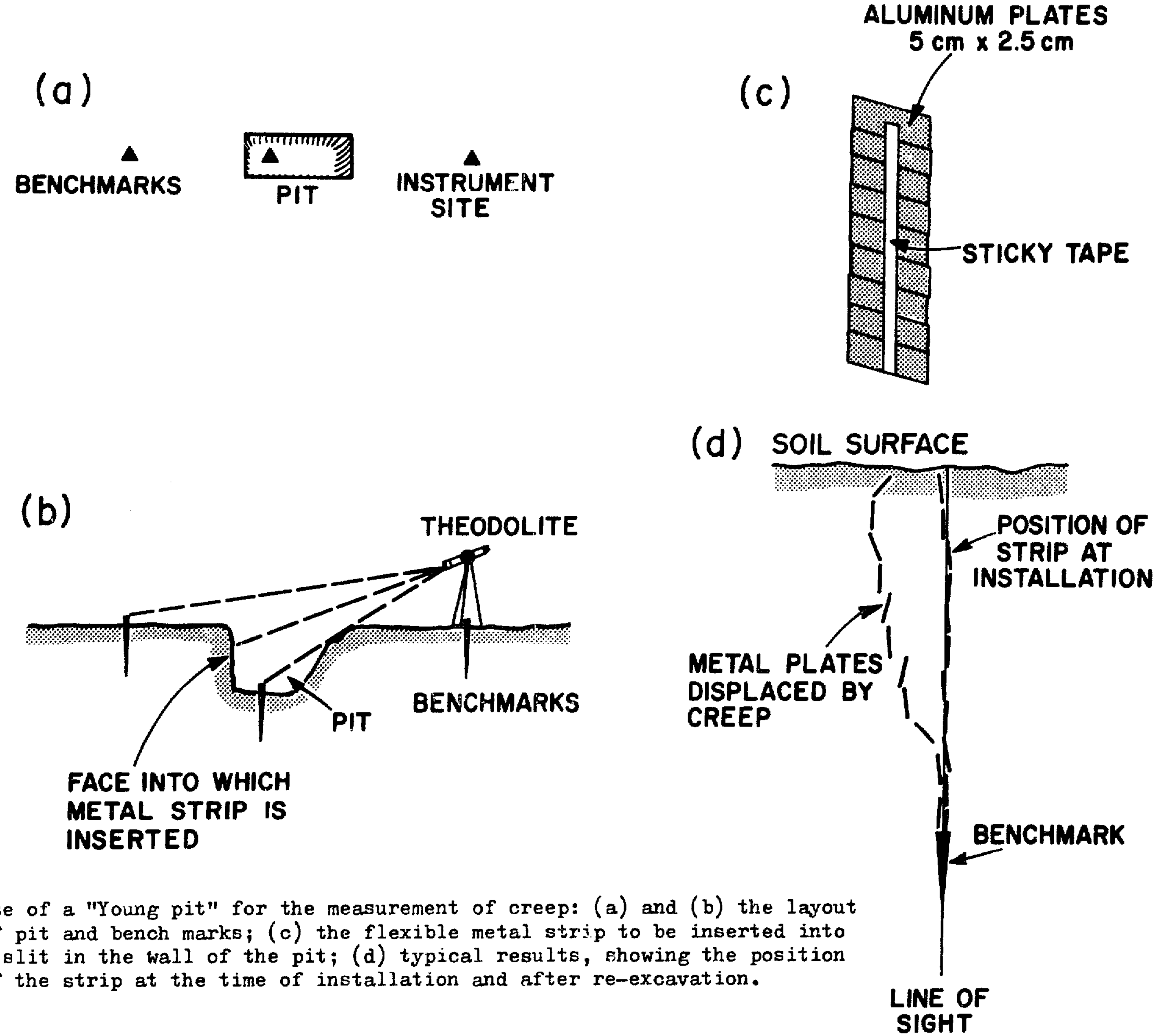


Figure 14. Use of a "Young pit" for the measurement of creep: (a) and (b) the layout of pit and bench marks; (c) the flexible metal strip to be inserted into a slit in the wall of the pit; (d) typical results, showing the position of the strip at the time of installation and after re-excavation.

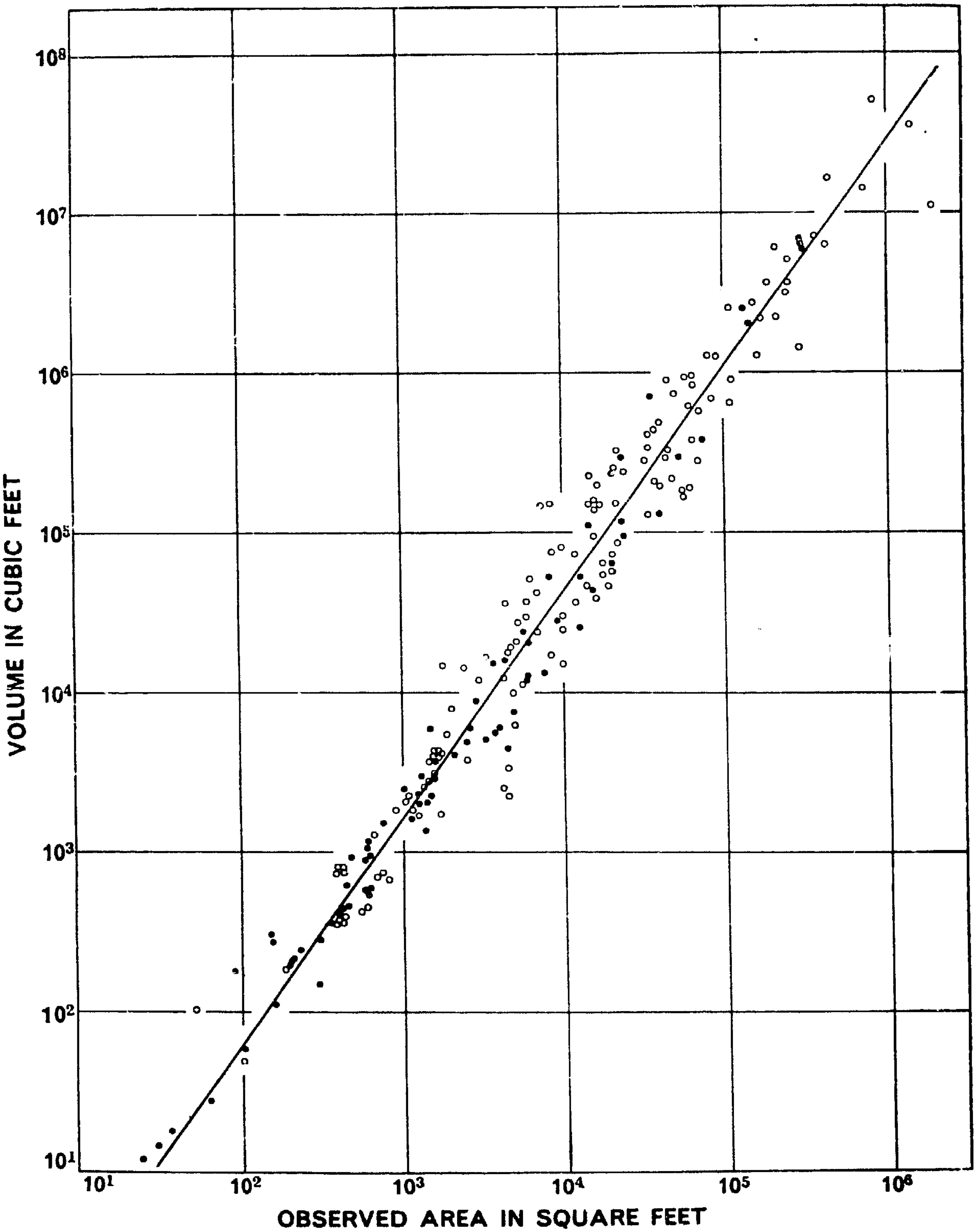


Figure 15. Relationship between area and volume of landslides in New Guinea. Source: Simonett (1967).

3.5.3 Large-scale Movements

Large-scale, more rapid mass movements include landslides, debris avalanches, earthflows and mudflows. These features can usually be mapped on aerial photographs, using either the scars themselves, the form of landslide deposits, or disturbances of the vegetation (25, 52). The investigator may wish only to count numbers of slides per unit area associated with various geologic, topographic or cultural features. Tubbs (47) for example, mapped landslides in Seattle and related their location to the underlying Quaternary stratigraphy. He was then able to identify zones of high landslide hazard throughout the urban area with the aid of topographic and geologic maps.

The areal extent of landslides can also be measured easily from aerial photographs, and gives a more quantitative picture of the extent of the process and of the resulting disruption. Corbett and Rice (7) placed a grid over aerial photographs and, by point-counting, estimated the area disturbed by shallow landslides on a range of hillslope gradients under two vegetative covers (see Table 2). Similar sampling schemes under other conditions could yield information that would be valuable for planning land-management practices to minimize erosion. By means of a relatively few field measurements (using a hand-level and tape, or visual estimation) it is possible to measure the volume of a sample of slides and to relate the volume to the area of individual failures (see Figure 15). Such a calibration curve might be needed for each physiographic region, depending upon the average depth and form of landslides. This technique provides a means of estimating the volume of sediment released by landslides, if the photogrammetry includes measurements of the number of landslides that reached a stream channel, or the proportion of landslide debris that has been removed by the stream. The volumes of earthflow and mudflow deposits can also be mapped on aerial photographs, or by plane-table.

Table 2: Relationship of the extent of shallow landslides to hillslope gradient and vegetative cover in southern California. Source: Corbett and Rice (7).

Slope class (%)	No. of slides per acre 1/		% of area covered by slides	
	Under brush	Under grass	Under brush	Under grass
<40	0	0	0	0
40-54	0	0.15	0	0.3
55-69	0.25	2.02	1.0	8.0
>70	0.88	4.09	3.2	13.3

1/ 1 acre = 0.4 hectare

Dating of old failures might be required for obtaining a long-term view of their contribution to catchment erosion, or of the frequency and size of landsliding before some change of land use. The success of various dating techniques depends upon the method used, the size and character of individual slides, the age of the slide, and any modifications that have occurred since the failure. In some cases dating of slides is easy in others it is not possible. The most accurate dating tool is obviously historical accounts of individual slides (1), or of large numbers of slides that can be dated and located from newspaper accounts. Tubbs (47) used a 30-year file of newspaper accounts to map and date several hundred landslides in Seattle. Records of road and railway maintenance in landslide-prone areas often contain useful data on the frequency and magnitude of hillslope failures.

Sequence of aerial photographs can also provide information about dates of landslide activity, though the low frequency of aerial surveys limits the usefulness of this method. Some landslides can be dated from their vegetation. The age of trees on the scar gives a minimum age for the slide. Around the edges of some landslide deposits, tree trunks may be scarred by fallen blocks. The number of growth rings that post-date such a scar is another indicator of the age of the failure. If the fallen debris contain organic material in an appropriate position, it can be dated by the radiocarbon method mentioned earlier (22).

In some cases, it is necessary to monitor large failures, or potential failure sites to provide an early warning of their occurrence or acceleration. Lines of stakes placed across an earthflow or other slow mass movement can be monitored periodically by a theodolite survey (41, 51).

3.6 Wind Erosion

The removal of soil by wind erosion has not yet been measured in many places and so little experience has been accumulated. Wind erosion is usually measured by repeated measurement at stakes, or is estimated in a qualitative erosion survey (U.S. Soil Conservation Service, 48) similar to that used for sheetwash. Degrees of damage caused by accumulation of windblown material are also classified in such a survey.

4. SUMMARY

The measurement of erosion by a variety of processes and at a variety of scales is relatively simple to perform. By comparison with the benefits to be gained from improved quantitative knowledge of the relation of soil loss to its controlling factors, a measurement programme is inexpensive. The value of such measurements increases with their duration and with the care with which they are planned. A great deal of thought should be given to the location of measurement sites, and also to ensuring that measurements are repeated and records stored in safe places for use in future planning.

5. ACKNOWLEDGEMENTS

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VII.
METHODS OF SOIL EROSION MONITORING FOR IMPROVED WATERSHED MANAGEMENT IN TANZANIA

by

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1. INTRODUCTION

In order to obtain reliable information on the types, extent and rates of erosion and sedimentation in Tanzania, an extensive study, reported by Rapp, Berry and Temple (1972) was carried out on one of the Dar-es-Salaam/Uppsala Universities' Soil Erosion and Research project studies. This paper reports some of the techniques used to measure erosion and sedimentation and some brief results obtained in two selected areas of the project.

The study areas represent two ecological zones: (1) steep, cultivated mountain slopes with perennial stream flow and (2) semi-arid savanna plains with a long dry season, severe shortage of water and seasonal stream flow (see Tables 1 and 2). Zone 1 is represented by a 19.1 km^2 instrumented catchment in the Ulangura mountains. Zone 2 is represented by the semi-arid and inselberg plains of the Dodoma region. 2/ The Ikowa, Msalatu, Imagi and Matumbulu catchments were studied in this region.

2. RUNOFF AND SEDIMENT SAMPLING ON THE MOROGORO RIVER

The flow of the Morogoro River is highly discontinuous with flash flood peaks. It rises suddenly in less than one minute at the stream gauge, stays as long as the rainfall in the catchment is intense and then gradually sinks to base flow level. Time of concentration is only in the order of 65 to 90 minutes.

Two types of suspended material are carried past the gauging station during each runoff event: channel-derived material and material eroded from slopes. The channel-derived material in steep catchments is probably carried beyond the station in a few stormflows. Sampling during the entire wet season is necessary to give a record of erosion of the catchment slopes. If an automatic sampler is used, it is important to sample both early and later parts of the flash floods in order to get a complete picture of not only the amounts but also the type of material carried - whether of channel or slope origin.

Runoff and suspended sediment was measured at a gauging station equipped with a Cipoletti weir during the period 1969 - 1971. Most of the sediment measurements were made with a point integrating, hand operated sampler of the Uppsala type (discussed in Nilsson, 1969). The device takes a one-litre sample and is easily constructed from readily available materials (Figure 1). 3/ However, manual sampling proved to be a difficult method to catch

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2/ "Inselberg" is a core of a former mountain left standing after geologic erosion.

3/ Details are available from B. Nilsson (see reference 4).

Table 1: Climatic records for the Morogroro station at 530 m a.s.l. and Morningside at 1450 m (only rainfall). Mean air temperature potential evaporation (E_o) and amount of clouds for the period 1947–1960 from Woodhead, 1968 (see reference 14). Data from E.A. Met. Dept.

Mean rainfall:	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
530 m a.s.l. (1931–60)	94	102	158	206	105	24	9	11	14	24	59	84	890
1450 m a.s.l. (1961–70)	132	175	274	525	245	115	104	96	123	170	250	182	2392
Mean air temp. (°C)	26.3	26.3	26.1	25.0	23.5	21.6	21.1	22.1	23.2	24.6	25.7	26.5	24.3
E_o (mm/month)	173	159	167	126	111	106	112	126	146	179	176	179	1760
Cloud (oktas)	5.5	5.7	5.7	6.1	6.1	5.4	5.3	5.2	5.2	5.0	4.9	5.2	–

Table 2: Climatic records, Dodoma met. station at lat. 6°10'S., long. 35°46'E., alt. 1120 m a.s.l. Mean rainfall in mm for 30 (1931–60) resp 42 (1929–1970) years. Mean air temp., wind speed, cloud amount and evaporation (E_o) for 10 years (1955–1964). Sources of data: E.A. Met. Dept., 1966, E.A. Met. records and Woodhead, 1968 (see reference 14).

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Mean rainfall, 30 yrs.	146	116	121	51	6	1	0	0	0	5	22	105	573
Mean rainfall, 42 yrs.	142	115	119	52	5	1	0	0	1	4	20	108	567
Average no. of rain days (30 yrs.)	12	10	11	7	2	0	0	0	0	1	2	9	54
Mean air temp. (°C)	23.8	23.7	23.5	23.1	22.1	20.5	19.8	20.5	22.1	23.5	24.8	24.6	22.7
Wind (km/day)	124	90	64	72	64	62	64	62	51	61	69	85	–
E_o (mm/month)	167	153	160	149	160	150	160	188	210	229	208	188	2123
Cloud (oktas)	5.7	5.5	5.7	5.9	5.1	3.9	3.5	3.4	3.1	4.0	4.6	5.3	–

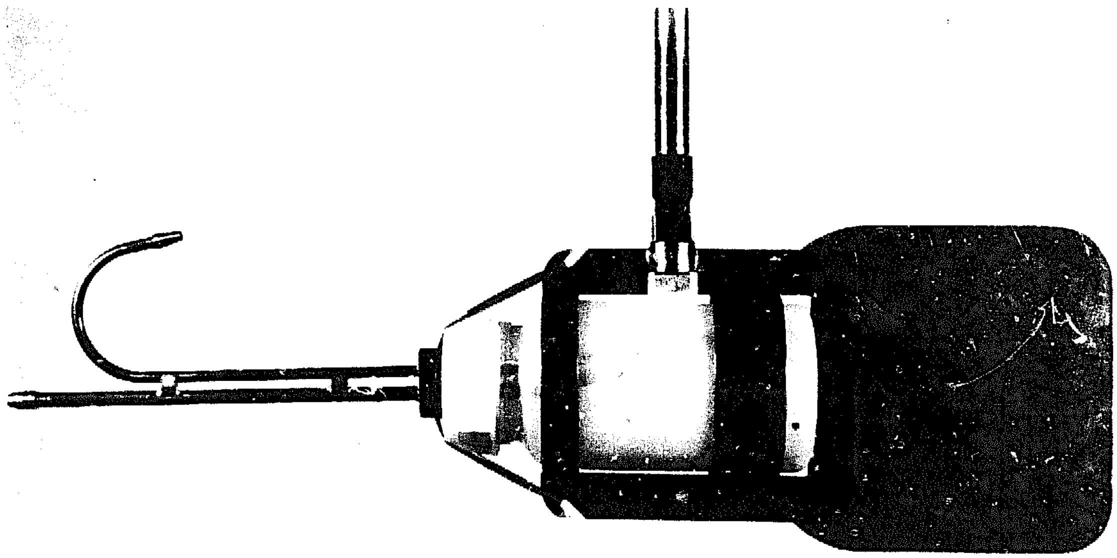

Figure 1. Hand-operated suspended-sediment sampler with interchangeable nozzle tips constructed locally. One-litre plastic bottles are used as sample containers (developed by B. Nilsson· see reference 4).

the high flow peaks of the Morogoro, which are irregular, short-lasting and often occur at night. Because of these difficulties, the number of flow peaks that were sampled and analyzed were not many, although there were sufficient observations to give the range of sediment concentration at various water stages. Figure 2 shows two complete series of water samples of flash flood peaks taken at 5 minute intervals, comparing streamflow to suspended sediment concentrations. Both series indicate the same pattern: (a) an initial low baseflow with very low sediment concentration; (b) then a rapid rise in only 10–30 seconds to the highest level, which essentially was maintained during and for about half an hour after, rain; (c) flow recession. During the first minutes of high flood, the samples had about 2 000 to 3 500 g/m^3 of sediment (or mg/l) and showed high content of medium sand and low content of finer material, evidently from the stream bed and, on the other hand, the samples from the main part of the flow and the falling stage contained a greater portion of fine-grained, brownish colloids, which most likely were material washed from the slopes.

In 1971, we tried to use an automatic sediment sampler of the Hayim 7 type, but due to practical difficulties of manpower and mounting, the instrument could not be used at Morogoro. It was later installed on the Msalatu catchment of the Dodoma region.

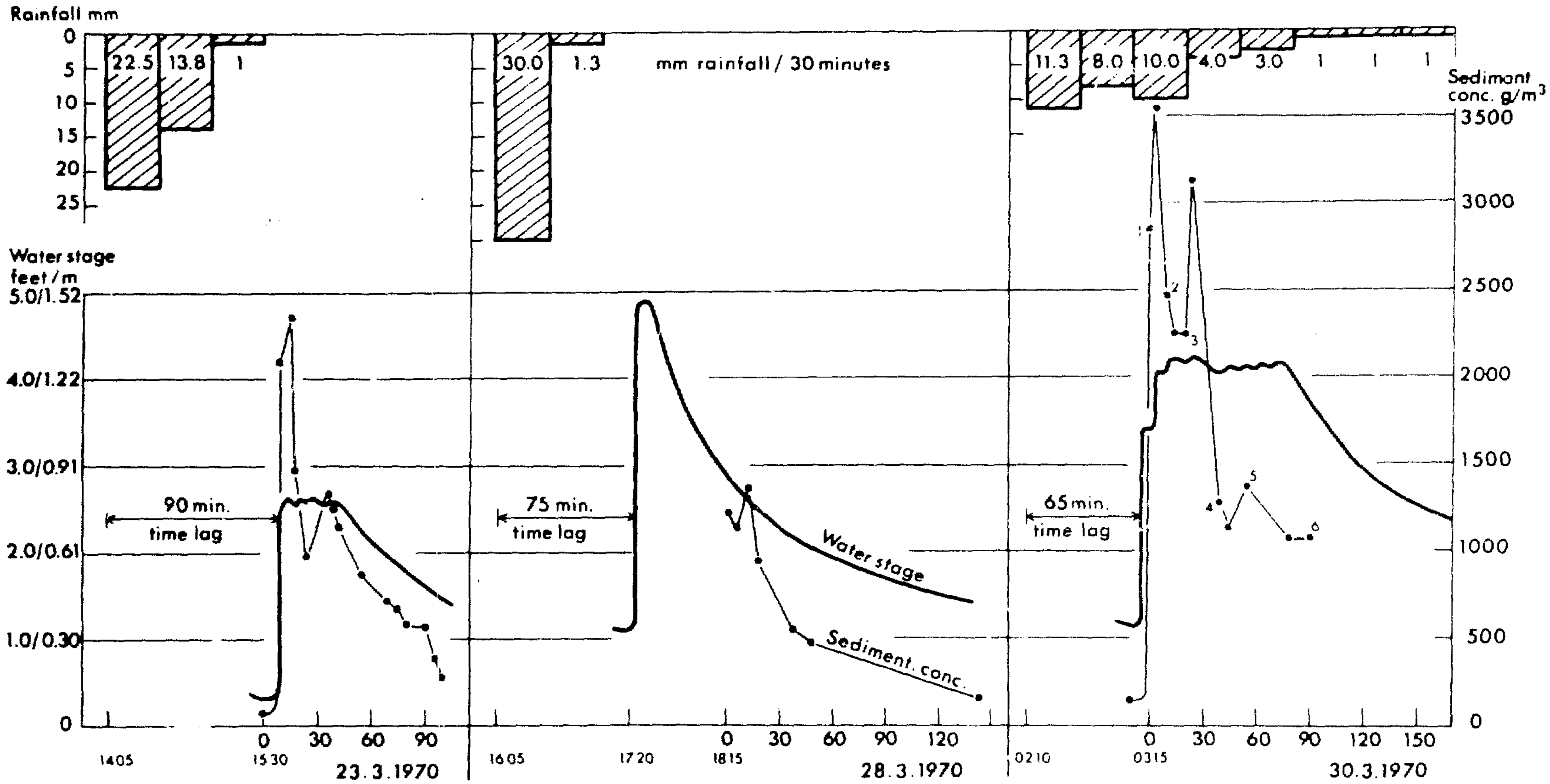

Figure 2. Rainfall at Morningside (mm/30 minutes), water stage and suspended-sediment concentration in Morogoro River at the gauging station during three flash floods on March 23, 28 and 30, 1970. Water stage curve from automatic recorder and reading of staff gauge.

Figure 3A. Automatic sediment sampler "Hayim 7" mounted in a gully, Msalatu catchment. (Photo C. Christiansson, 1971). Note steep crusted gully sides and sandy bed.

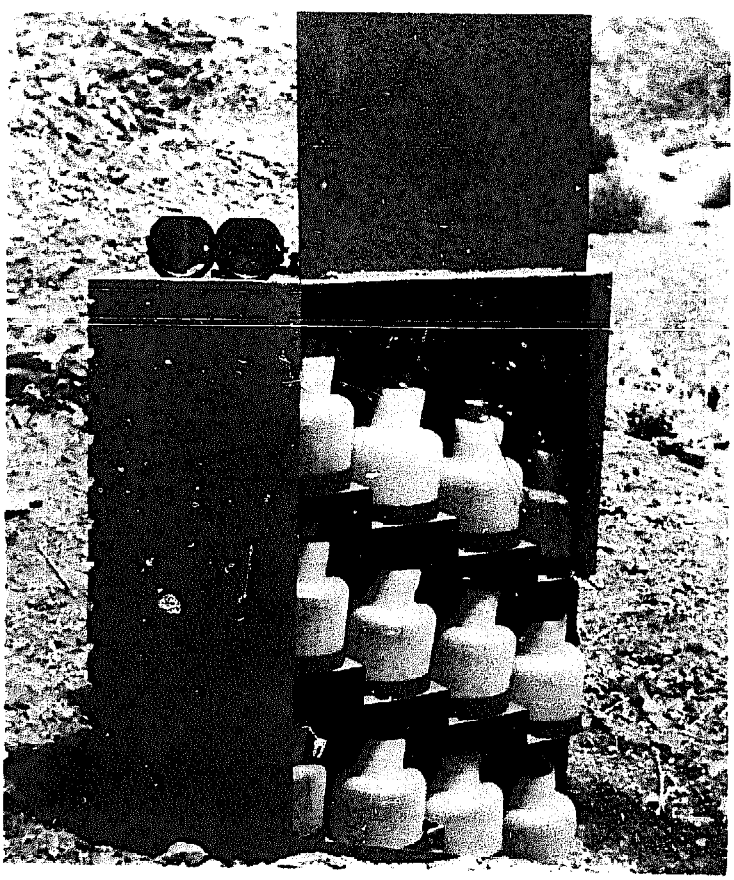

Figure 3B. Sampler "Hayim 7" opened. (Photo A. Rapp, 1968).

3. AUTOMATIC SEDIMENT SAMPLING IN THE DODOMA REGION

The Hayim 7 automatic sampler was installed about 150 m from the inflow end of a reservoir on the Msalatu catchment in the sandy bed of the channel in a narrow gully section with steep, crusted side walls (Figure 3A). The Hayim 7 is primarily designed for desert streams, where floods are violent and short-lived (details are in reference 7, Schick). It is a modification of the standard automatic single stage sediment sampler developed in the United States. The sampler takes one-litre samples during the rising stage of a flow event at twelve intervals of 5 cm above the channel bed.

Construction details of the samplers are shown in Figure 3B. Twelve, one-litre plastic bottles are mounted in a sheet metal housing. The air intake pipes to the sample bottle are 7 mm inside diameter and 9 mm outside diameter. Air leaves the bottles via plastic tubes which are contained within an exhaust pipe mounted to the top of the housing. The filling time is about one minute per sample (Schick, personal information).

When checked after two flash floods, the sample bottles contained sediment, ranging from 15 000 to 75 000 g/m^3 (mg/l). Similar sediment concentrations ranging from 10 000 to 131 000 g/m^3 were reported from flash floods in the Negev desert, according to data from another Hayim automatic sampler (8). The concentration of sediment in the samples at Msalatu are of the same range as those measured in runoff water from erosion plots at Mpwapwa by Staples. There, the average annual concentrations during two years of recordings ranged from 25 000 to 87 000 g/m^3 (reference 11). This included suspended load and bed load in slope wash from 50 m^2 erosion plots.

The grain sizes of sediment loads in the channel indicate rather unsorted transportation, including clay (25-40%), silt (30-50%) and sand (15-50%). The high proportions of clay and silt indicate that most of the suspended sediments do not come from the sandy channel bed, but from the inter-gully areas or the gully walls. Which of the possible sources is the most important could be checked by continued recordings.

4. ANALYSIS OF SEDIMENT SAMPLES

In our studies the one-litre samples were filtered through "Whatman" filter paper No. 40 (the amount of suspended sediment that passed through the filter paper was found to be negligible). After drying the filter paper, the concentration of suspended sediment was determined as the difference of filter paper weight before and after filtration. This method is rather inaccurate when the sediment concentration is low, but acceptable when the concentration is higher than 1 000 g/m^3.

5. SURVEYS

The inselberg plains of the Dodoma region, as many other arid regions, are areas of erratic rainfall, droughts, overgrazing and repeated famines (1, 10). Streams are ephemeral and there are not long-term gauging records of small catchment streams available. Consequently, our investigation of water erosion and sedimentation could not be based on sediment sampling in streams as in the Morogoro study but had to focus on: (a) sedimentation surveys of reservoirs combined with (b) catchment erosion surveys, described below.

5.1 Reservoir sedimentation surveys

Man-made and natural lakes act as sediment traps and store part of the sediment eroded from the watershed catchment (Figure 4). The volume of sediment deposited on the bottom of the reservoirs of the four catchments on the Dodoma region was calculated from surveyed transects across the reservoirs during the dry season. The transects were made by manual soundings from a rubber boat and by levelling on the dry parts of the bottom (see also the paper by Rausch and Heinemann in this publication, on reservoir surveys). The volume of sediment deposited was calculated by comparisons between these surveys and earlier maps or transects. Results of the survey of the Matumbulu reservoir are shown in Figure 5,

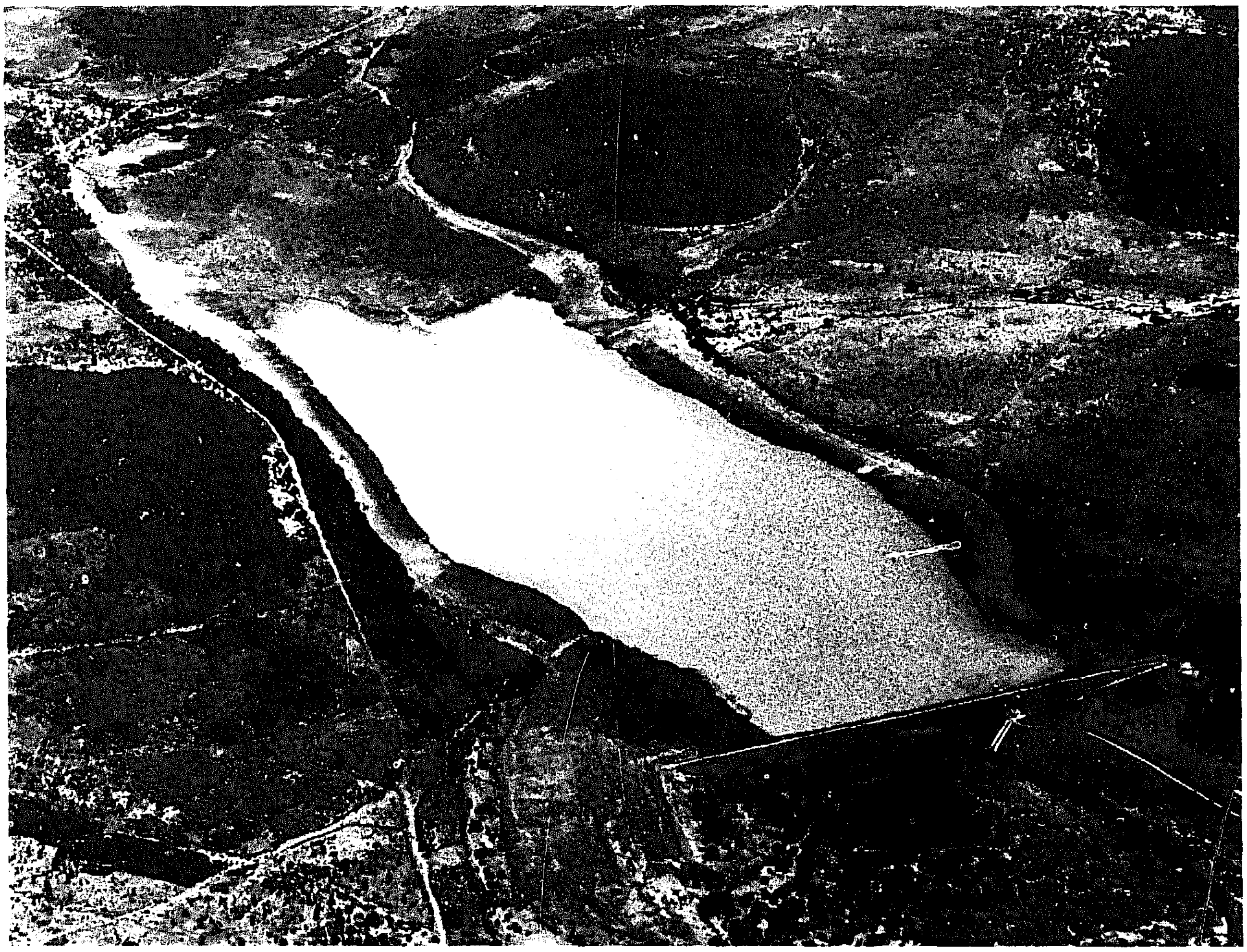

Figure 4. Oblique air photo of Ikowa dam and reservoir showing sediment problem. Dark, delta-like surface at the upper end of the reservoir is exposed bottom with clayey sediments. Mtwango inselberg with dark miombo woodland in centre of picture. Level of reservoir is 2.26 m below full storage level. (Photo A. Rapp, Sept. 25, 1971).

as an example. During the period 1962 - 1971, sediment accumulated in this reservoir at a rate of 13 200 m^2 per year for a total of 119 000 m^2. At this rate, the expected life of the reservoir is only 30 years.

For comparison sake, the relation between sediment yield and size of drainage area is shown for 73 small, semi-arid catchments in Wyoming, western U.S.A., from studies by Schumm and Hadley (9), with the 5 catchments in Tanzania superimposed on their figure. All the Tanzanian catchments have higher sediment than the American catchments, even though rainfall intensities are similar. Matumbulu stands out as a catchment with particularly high sediment yield in relation to its size. The implications of man-caused erosion due to differences in land use are clear. (Fig. 6)

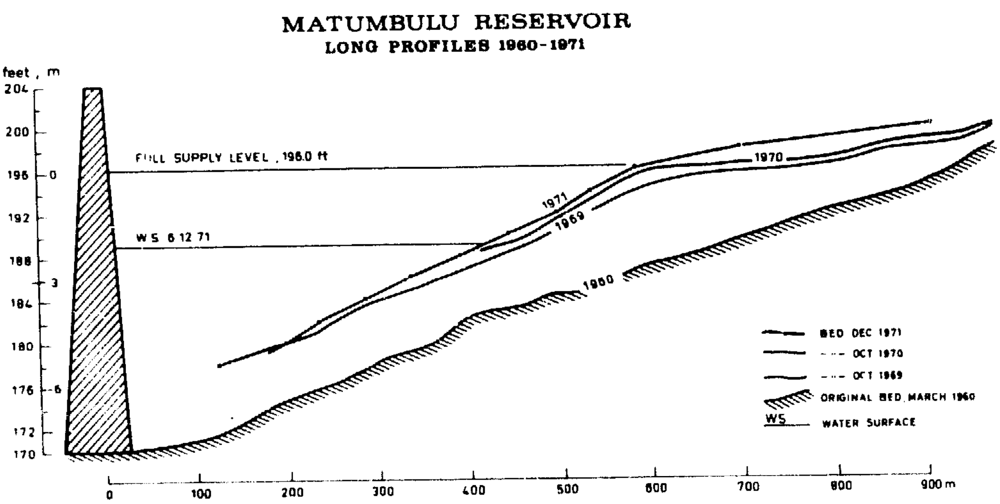

Figure 5. Matumbulu reservoir. Long profiles of 1960, 1969, 1970 and 1971. Surveys in 1960 by WD & ID, other years by DUSER teams. Note the break in slope of delta at the full supply level (flood pool).

5.2 Erosion surveys

The surveys of reservoir sedimentation should be combined with inventories of the sources of erosion and causes of sedimentation in the catchment if the pattern of erosion and its intensity is to be understood. The purpose of the erosion survey is to locate areas of erosion and deposition, distinguish their type and, if possible, intensity. The relative importance of different types of erosion is fundamental to developing conservation strategies.

The inventories in this study were made by air photo interpretation and by field checking, mainly as slope profiles from valley bottom to hilltop. The slope profiles include observations of slope angles, vegetation cover, soils, land use and forms of erosion and sedimentation. Maps of land use and zones of erosion and sedimentation were made over four catchments of the Dodoma region by interpretation of available air photos from 1960. Catchment areas and percentages of different types of land were measured on these maps and tabulated. The map developed from an erosion survey of the Matumbulu catchment is shown in Figure 7 as an example.

Major types of erosion also are illustrated in the survey maps of Figure 8. These field observations underscored the need for conservation measures to stop erosion, for example, grass barriers, terracing, cover crops, mulching, protective forest, controls against road erosion and other practices of watershed conservation.

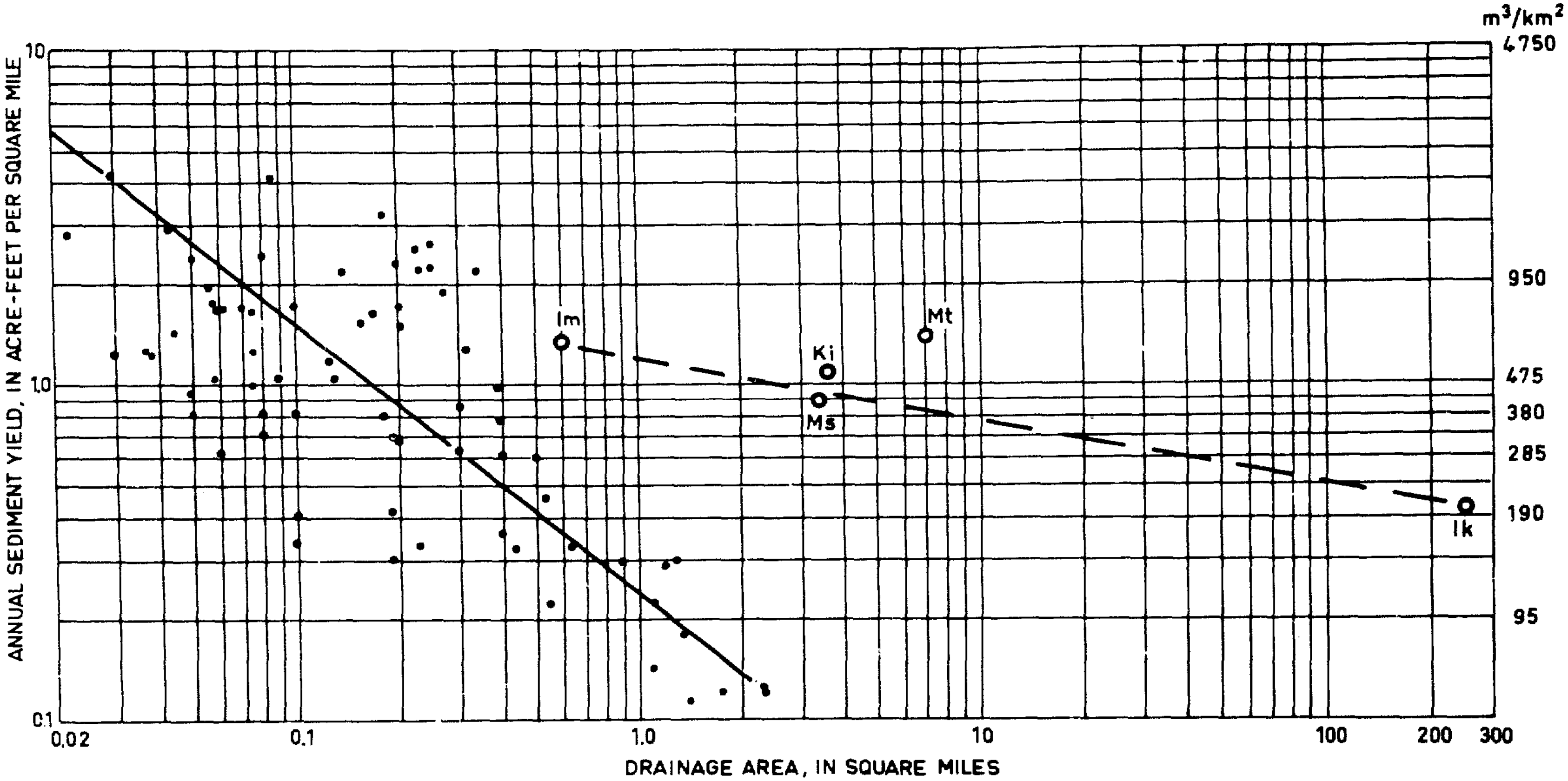

Figure 6. Relation of mean annual sediment yield to drainage area for the five catchment basins in Tanzania (open circles) compared to seventy-three semi-arid basins (dots) in eastern Wyoming, U.S.A. The latter after Schumm and Hadley, 1961. The basin data of Ik, Ms and Im have the longest records and the most similar environmental characteristics of the Tanzanian cases. They are connected by a dashed line. Decrease of sediment yield with increasing drainage area is evident in both groups but is less marked in the Tanzanian cases. 1 acre-foot = 1233.5 m^3. 1 square mile = 2.6 km^2, with m^3/km^2 shown on the right-hand edge.

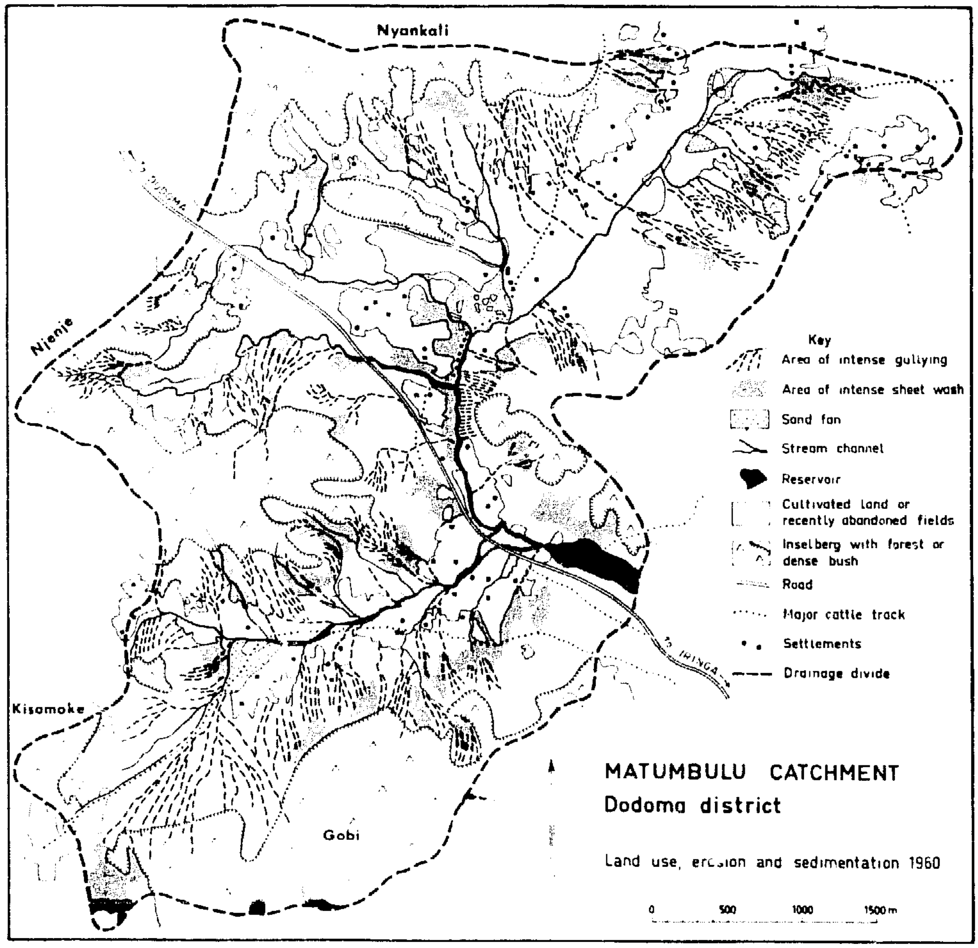

Figure 7. Example of map of land use, erosion and sedimentation from the Matumbulu catchment showing gullied upper pediments with intense sheet erosion cultivated lower areas, stream channels with sand fans and reservoir sedimentation (from studies by A. Rapp, D.H. Murray-Rust, C. Christiansson and L. Berry).

6. RESULTS AND RECOMMENDATIONS

Reservoir sedimentation rates in the cases investigated correspond to annual sediment yields of 200 - 730 m^3/km^2 averaged over the longest periods of available records. The figures of sediment yield per km^2 decrease with increasing drainage area, due to sedimentation in the catchment. Therefore, sediment yields from small catchment basins of a few km^2 in area reflect most closely the erosion in the catchment.

The most important process of erosion in the semi-arid catchments of Dodoma and Arusha catchments is sheet wash from overgrazed land and unprotected cultivations. Gully erosion is probably connected with rare and extremely intense rainstorms. Studies of when and how gullies are cut and how they function as drainage lines for water and sediment should continue and should provide a basis for the establishment of efficient methods of gully control.

Reservoir surveys to document the rate and type of sedimentation and to establish the remaining life of reservoirs should be undertaken as standard practice for all existing and planned reservoirs in semi-arid areas. Reservoir maps and profiles should be made, and sedimentation pegs established when a development project starts, so that through later comparisons one can determine how the project has affected the area.

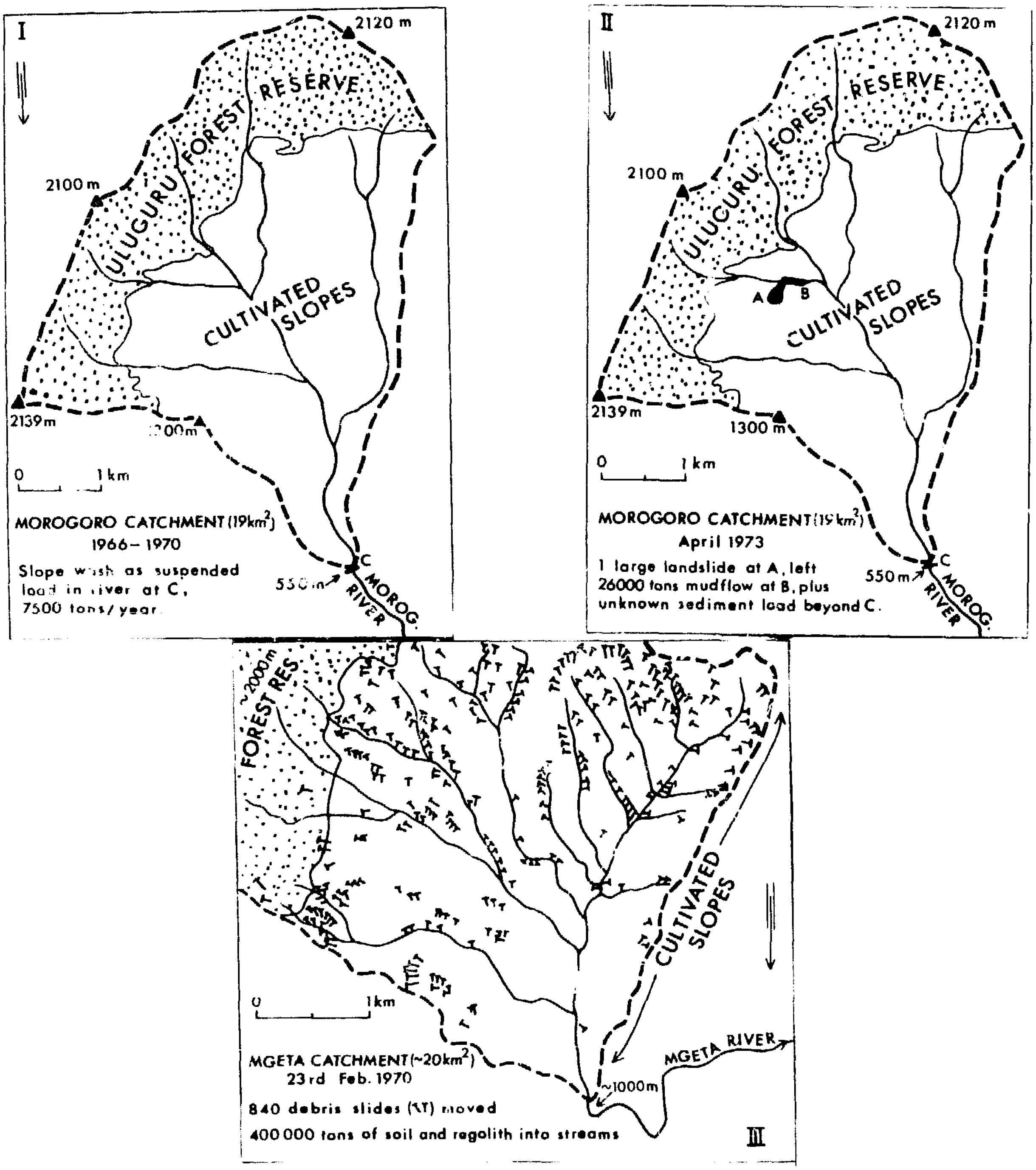

Figure 8. Three maps showing three major types of erosion on deforested and cultivated slopes in tropical mountains, as represented by the Uluguru Mountains in Tanzania.

Map I. Annual "average" slope wash 1966–1970 from cultivated slopes caused a soil loss of 7500 tons/year, measured as suspended load in the Morogoro River (from Rapp et al., 1972).

Map II. Large landslide within same watershed area as on Map I, in April 1973. It blocked the water intake of Morogoro town, silted up the water pipes and damaged the water supply for weeks (from Lundgren and Rapp, 1974).

Map III. A large number of small landslides triggered by a heavy rainstorm of 100 mm on Feb. 23, 1970. A few landslides occured in the forest reserve, more than 800 on deforested slopes below the forest reserve boundary.

Improved grass management in the semi-arid catchments is the best general method of decreasing soil erosion and increasing the life of the reservoirs.

In summary, we recommend continued and extended studies of the water and sediment budget in catchments of all sizes in semi-arid regions. Such studies will provide a basis for better knowledge of the following problems:

a) The range of losses of water, soil, and plant nutrients from areas under different types of land use, as compared to good grassland management.

b) The importance of catastrophic erosional events due to heavy, infrequent rainstorms in comparison with average annual losses. Particular emphasis should be placed on the problems of gully erosion in relation to sheet erosion.

c) The time needed for recovery of soil, vegetation and economy after excessive erosion.

d) The best and least expensive conservation practices in semi-arid lands, their implementation and maintenance in a long-term perspective.

e) The rate of reservoir sedimentation and the distribution, texture and structure of the deposits. Such studies provide important information for many purposes, such as erosion in catchment, prognosis of useful life of reservoir and possible use of sand-filled reservoirs for ground water storage.

7. ACKNOWLEDGEMENTS

Special appreciation is extended to Dr. A. Kesseba and his assistants at the Department of Agricultural Chemistry, Morogor, to V. Axelsson and to Dr. H. Kuschel, Dodoma, for their valuable contributions to this work.

<u>Note</u>: Original materials supplied by the author have been revised by the editor and selected from several reports which were provided in order to emphasize the techniques which were used, rather than the results <u>per</u> <u>se</u>. The reader is referred to the original reports, given in the reference list, for further details on the results obtained.

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VIII. PREDICTING SOIL LOSSES DUE TO SHEET AND RILL EROSION

by

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1. INTRODUCTION

At present the Universal Soil Loss Equation (U.S.L.E.) is the mathematical model most often used to predict soil losses due to areal erosion. Especially in the U.S.A. the equation has been adopted by the Soil Conservation Service (SCS) for work concerned with areal erosion. For many years the equation, developed by Wischmeier and his associates from 1957 onwards (i.e., 1, 3, 6, 7, 8, 9, 10, 11), has been used on agricultural lands and from 1971 on construction sites and from 1972 onwards also for range and forest lands. Caution: Since the U.S.L.E. has been developed in the U.S.A., through statistical analyses of erosion measurements on experimental plots, correlations are very good for conditions in North America. Caution is needed when applied outside the U.S.A. because some of the relations used do not always apply in different environments. For instance, the rainfall factor (R) has a high correlation with soil loss on Java, Indonesia, but a poor correlation with soil loss in Benin. Therefore, the equations may need to be adapted to local conditions, especially the significance of the rainfall factor (R) and the cropping-management factor (C) need to be checked. Also, although the U.S.L.E. is a rather simple steady-state model, a rather sophisticated data set is needed, especially, again, with respect to rainfall (daily records over a number of years), vegetation and, to a lesser extent, to soil conditions. If such data set is not available, it is not advisable to try to use the U.S.L.E. but simpler, especially visual techniques, for example, the ones outlined in the paper by Dunne, also in this series.

Even when sufficient data are available some caution is needed because little experience has been gained on slopes over 20° or longer than 150 m (500 ft).

This paper is mainly based upon Wischmeier and Smith: Agriculture Handbook No. 282 (11), unless otherwise indicated.

Example: An example is given in Section 3.5 of this paper showing how to apply the U.S.L.E. in watershed planning.

1/ Technical Officer Soil Conservation

2. DESCRIPTION OF THE EQUATION AND EVALUATION OF THE FACTORS

2.1 Basic equation

The basic equation is a simple one and is written as:

A = R K L S C P .... [1], in which

A = computed soil loss per unit area; obtained by multiplication of the remaining factors.

R = rainfall factor; the number of erosion index units (EI - units) in the period of consideration. The erosion index is a measure of the erosive force of specific rain.

K = soil erodibility factor; the erosion rate per unit of erosion index for a specific soil, in a cultivated continuous fallow on a 9 percent slope, 22.1 m (72.6 ft) long.

L = slope length factor; the ratio of soil loss from the field slope length to that from a 22.1 m (72.6 ft) length on the same soil type and gradient.

S = slope gradient factor; the ratio of soil loss from the field gradient to that from a 9 percent slope, on the same soil type and slope length.

C = cropping-management factor; the ratio of soil loss from a field with specific cropping and management to that from the fallow condition on which the factor K is evaluated.

P = erosion-control practice factor; the ratio of soil loss with contouring, stripcropping or terracing to that with straight-row farming, up-and-down slope.

Evaluation of the Factors: the U.S.L.E. has been developed in the pound-foot-second system. In this presentation both metric-units (m-units) as well as pound-foot-second units (pfs-units) will be given, the latter between brackets.

2.2 Rainfall factor: R

The rainfactor (R) is Wischmeier's (6) erosion index (EI_{30}-index), i.e., the total kinetic energy of a rainstorm (E) times its maximum intensity over 30 minutes (I_{30}), divided by 100.

In order to arrive at the total kinetic energy, the precipitation is divided into periods with approximately the same rainfall intensity. For each period the kinetic energy is calculated according to:

E = 210.2 + 89 log I (Joules/m^2 per cm of rain) ..... [2,M], or

E = 916 + 331 log I (foot tons/acre per inch of rain) ..... [2,pfs] 1/, in which

E = kinetic energy in Joules/m^2 per cm of rain (foot-tons/acre per inch of rain).

I = average rainfall intensity of the considered period in cm/hr (inches/hr).

1/ "2,M" shows formula number and indicated "metric system" whereas 2,pfs is formula number 2 as well, but in the pound-foot-second system.

Also tables have been developed (10) from which the kinetic energy can be read. These tables are given as Table 1a (in M-units) and Table 1b (in pfs-units). (Caution: Formula [2] and Table 1 apply only to non-orographic rain).

In order to arrive at the total kinetic energy of a storm, the kinetic energy calculated for each period is multiplied by the cm (inches) of rain that fell during that period. Finally these products are summed.

To obtain the R-value the total kinetic energy is multiplied by twice 1/ the maximum average 30-minute intensity (I_{30}) and divided by 100. The maximum average 30-minute intensity can be obtained from a raingauge record as shown in Figure 1.

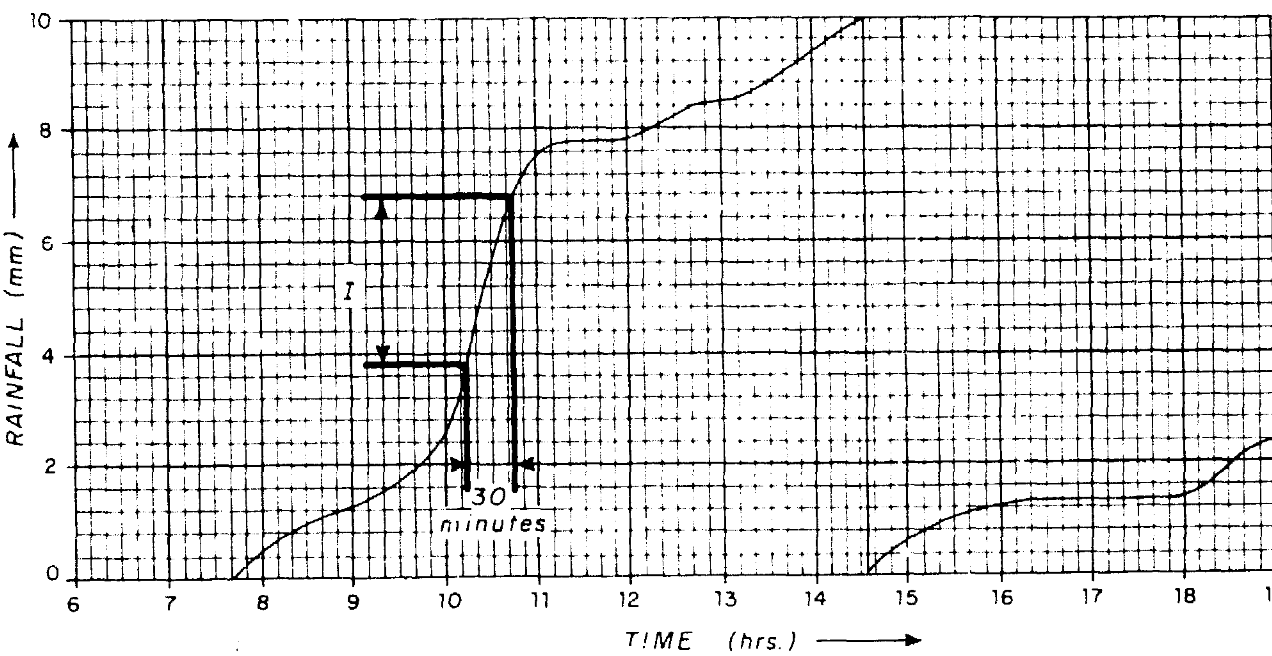

Figure 1. The 30-minute period with the steepest slope of the pluviograph is singled out and the amount of precipitation (I) is read on the vertical axis. I_{30} equals cm (inches)/0.5 hr (After Hudson (2)).

In order to arrive at the value of the rainfall factor (R) for a longer period, the EI-indices of the individual storms need to be summed. For the U.S.A. (east of the Rocky Mountains) enough data were available to calculate the average yearly R-values, which enabled compilation of an Iso-erodent map (Figure 2). Also for areas with a same distribution of erosion indices over the year, Erosion-Index Distribution curves could be drawn (Figure 3). These distribution curves are necessary for the full appreciation of the protective effect of field crops throughout the year.

1/ The 30-minute intensity is multiplied by two in order to convert intensity/½ hr into intensity/hr.

TABLE 1.a: KINETIC ENERGY OF NON-OROGRAPHIC RAIN
(Part 1) (Joules/m^2 per cm of rain)

Intensity cm/hr	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
0.0	0.00	32.3	59.09	74.76	85.88	94.51	101.50	107.51	112.68	117.23
0.1	121.30	124.98	128.35	131.44	134.31	136.97	139.47	141.81	144.02	146.11
0.2	148.09	149.98	151.78	153.49	155.14	156.72	158.23	159.69	161.10	162.45
0.3	163.76	165.03	166.26	167.45	168.60	169.72	170.81	171.87	172.90	173.91
0.4	174.88	175.84	176.77	177.68	178.57	179.44	180.29	181.12	181.93	182.73
0.5	183.51	184.27	185.02	185.76	186.48	187.19	187.89	188.57	189.25	189.91
0.6	190.56	191.19	191.82	192.44	193.05	193.65	194.24	194.82	195.39	195.96
0.7	196.51	197.06	197.60	198.14	198.66	199.18	199.69	200.20	200.70	201.19
0.8	201.68	202.16	202.63	203.10	203.56	204.02	204.47	204.92	205.36	205.80
0.9	206.23	206.66	207.08	207.50	207.91	208.32	208.72	209.12	209.52	209.91
1.0	210.30	210.69	211.07	211.44	211.82	212.19	212.55	212.92	213.28	213.63
1.1	213.98	214.33	214.68	215.02	215.37	215.70	216.04	216.37	216.70	217.02
1.2	217.35	217.67	217.99	218.30	218.62	218.93	219.23	219.54	219.84	220.14
1.3	220.44	220.74	221.03	221.32	221.61	221.90	222.19	222.47	222.75	223.03
1.4	223.31	223.58	223.85	224.13	224.39	224.66	224.93	225.19	225.45	225.71
1.5	225.97	226.23	226.48	226.74	226.99	227.24	227.49	227.74	227.98	228.22
1.6	228.47	228.71	228.95	229.19	229.42	229.66	229.89	230.12	230.35	230.58
1.7	230.81	231.04	231.26	231.49	231.71	231.93	232.15	232.37	232.59	232.80
1.8	233.02	233.23	233.45	233.66	233.87	234.08	234.29	234.49	234.70	234.91
1.9	235.11	235.31	235.51	235.72	235.91	236.11	236.31	236.51	236.70	236.90
2.0	237.09	237.28	237.48	237.67	237.86	238.05	238.23	238.42	238.61	238.79
2.1	238.98	239.16	239.34	239.53	239.71	239.89	240.07	240.25	240.42	240.60
2.2	240.78	240.95	241.13	241.30	241.47	241.64	241.82	241.99	242.16	242.33
2.3	242.49	242.66	242.83	243.00	243.16	243.33	243.49	243.65	243.82	243.98
2.4	244.14	244.30	244.46	244.62	244.78	244.94	245.09	245.25	245.41	245.56
2.5	245.72	245.87	246.02	246.18	246.33	246.48	246.63	246.78	246.93	247.08
2.6	247.23	247.38	247.53	247.68	247.82	247.97	248.12	248.26	248.40	248.55
2.7	248.69	248.83	248.98	249.12	249.26	249.40	249.54	249.68	249.82	249.96
2.8	250.10	250.24	250.37	250.51	250.65	250.78	250.92	251.05	251.19	251.32
2.9	251.45	251.59	251.72	251.85	251.98	252.11	252.25	252.38	252.51	252.64

TABLE 1.a: (Part 2)

Intensity cm/hr	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
3	252.76	254.03	255.26	256.45	257.60	258.72	259.81	260.87	261.90	262.91
4	263.88	264.84	265.77	266.68	267.57	268.44	269.29	270.12	270.93	271.73
5	272.51	273.27	274.02	274.76	275.48	276.19	276.89	277.57	278.25	278.91
6	279.56	280.19	280.82	281.44	282.05	282.65	283.24	283.82	284.39	284.96
7	285.51	286.06	286.60	287.14	287.66	288.18	288.69	289.20	289.70	290.19
8	290.68	291.16	291.63	292.10	292.56	293.02	293.47	293.92	294.36	294.80
9	295.23	295.66	296.08	296.50	296.91	297.32	297.72	298.12	298.52	298.91
10	299.30	299.69	300.07	300.44	300.82	301.19	301.55	301.92	302.28	302.63
11	302.98	303.33	303.68	304.02	304.37	304.70	305.04	305.37	305.70	306.02
12	306.35	306.67	306.99	307.30	307.62	307.93	308.23	308.54	308.84	309.14
13	309.44	309.74	310.03	310.32	310.61	310.90	311.19	311.47	311.75	312.03
14	312.31	312.58	312.85	313.13	313.39	313.66	313.93	314.19	314.45	314.71
15	314.97	315.23	315.48	315.74	315.99	316.24	316.49	316.74	316.98	317.22
16	317.47	317.71	317.95	318.19	318.42	318.66	318.89	319.12	319.35	319.58
17	319.81	320.04	320.26	320.49	320.71	320.93	321.15	321.37	321.59	321.80
18	322.02	322.23	322.45	322.66	322.87	323.08	323.29	323.49	323.70	323.91
19	324.11	324.31	324.51	324.72	324.91	325.11	325.31	325.51	325.70	325.90
20	326.09	326.28	326.48	326.67	326.86	327.05	327.23	327.42	327.61	327.79
21	327.98	328.16	328.34	328.53	328.71	328.89	329.07	329.25	329.42	329.60
22	329.78	329.95	330.13	330.30	330.47	330.64	330.82	330.99	331.16	331.33
23	331.49	331.66	331.83	332.00	332.16	332.33	332.49	332.65	332.82	332.98
24	333.14	333.30	333.46	333.62	333.78	333.94	334.09	334.25	334.41	334.56

TABLE 1.b: KINETIC ENERGY OF NON-OROGRAPHIC RAIN 1/
(Foot-tons/acre per inch of rain)

Intensity in/hr	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0	254	354	412	453	485	512	534	553	570
0.1	585	599	611	623	633	643	653	661	669	677
0.2	685	692	698	705	711	717	722	728	733	738
0.3	743	748	752	757	761	765	769	773	777	781
0.4	784	788	791	795	798	801	804	807	810	814
0.5	816	819	822	825	827	830	833	835	838	840
0.6	843	845	847	850	852	854	856	858	861	863
0.7	865	867	869	871	873	875	877	878	880	882
0.8	884	886	887	889	891	893	894	896	898	899
0.9	901	902	904	906	907	909	910	912	913	915
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	916	930	942	954	964	974	984	992	1000	1008
2	1016	1023	1029	1036	1042	1048	1053	1059	1064	1069
3	1074	1079	1083	1088	1092	1096	1100	1104	1108	1112
4	1115	1119	1122	1126	1129	1132	1135	1138	1141	1144
5	1147	1150	1153	1156	1158	1161	1164	1166	1169	1171
6	1174	1176	1178	1181	1183	1185	1187	1189	1192	1194
7	1196	1198	1200	1202	1204	1206	1208	1209	1211	1213
8	1215	1217	1218	1220	1222	1224	1225	1227	1229	1230
9	1232	1233	1235	1237	1238	1240	1241	1243	1244	1246

1/ From: Wischmeier and Smith (10).

Figure 2. Eastern part of the Iso-erodent map for the U.S.A., east of the Rocky Mountains, showing average annual values of the rainfall factor (R) (in pfs-units). (Reproduced from Wischmeier and Smith (11), Figure 1, pp. 6-7).

A good correlation has been reported (7) between average yearly EI_{30}-index and the product of the average annual rainfall times the 2-year 1-hour rainfall amount, times the 2-year 24-hour rainfall amount, or:

EI_{30} = $f(P \times I_1^{2yr} \times I_{24}^{2yr})$ ..... [3], in which

P = annual precipitation

I_1^{2yr} = 1 hour rainfall amount with a return period of 2 years.

I_{24}^{2yr} = 24 hour rainfall amount with a return period of 2 years.

The regression equations have to be calculated separately for each region under study. The relations can be used to approximate EI_{30}-values for stations that have no automatic recording raingauges (7).

According to Hudson (2) the EI_{30}-index is less suited to regions which receive a large portion of their rain with high intensities. For these tropical and subtropical regions he proposed the KE>25-index. In this system all rain with an intensity of less than 25 mm (1 inch)/hr is disregarded. For the remainder the kinetic energy is calculated according to [2] or read from Table 1. The total kinetic energy equals the value of the KE>25-index. So the kinetic energy is not multiplied by the 30-minute intensity (I_{30}).

2.3 Soil erodibility factor: K

The soil erodibility factor K can be evaluated on experimental plots by solving the equation:

$K = \frac{A}{RLSCP}$ .... [4] for non-standard conditions, or

$K = \frac{A}{R}$ .... [5] for standard conditions. 1/

More recently a nomograph has been devised (9) that enables evaluation of the K-value from five simple soil-parameters: (i) percent silt + very fine sand, (ii) percent sand, (iii) percent organic matter, (iv) structure, and (v) permeability. The parameters are introduced in this sequence in the nomograph (Figure 4). For soil erodibility evaluations "percent silt + very fine sand" is defined as: 0.002 mm - 0.10 mm and percent sand as: 0.10 mm - 2,0 mm particle size.

Structure is coded as: 2/

1 = very fine granular and very fine crumb (< 1 mm)

2 = fine granular and fine crumb (1 mm-2 mm)

3 = medium granular, medium crumb (2 mm-5 mm) and coarse granular (5 mm-10 mm)

4 = platy, prismatic, columnar, blocky and very coarse granular.

The values for: percent silt + very fine sand, percent sand, percent organic matter and structure are average values for the upper 15 to 20 cm (6-7 inches). The value for permeability refers to the profile as a whole.

1/ Standard conditions are: slope gradient = 9% : slope length = 22.1 m (72.6 ft) : cultivated continuous fallow, ploughing up-and-down the slope. Under standard conditions: L=S=C=P=1.

2/ The classification given here is slightly different from the one given by Wischmeier et al. (9): it is taken from the Soil Survey Manual (5) pp. 225-230.

For permeability the following codification is used: 1/

1 = rapid to very rapid

2 = moderately rapid

3 = moderate

4 = moderately slow

5 = slow

6 = very slow

General permeability classification guides are given in the USDA Soil Survey Manual (5), pp. 167-168, but according to Wischmeier et al. laboratory determinations are not necessary in general. They supplemented the general rules with the following "rules of thumb" for codes 4, 5 and 6:

- fragipan soils are coded 6 ;
- more permeable surface soils underlain by massive clay or silty clay are coded 5 ;
- moderately permeable surface soils underlain by a silty clay or silty clay loam having a weak subangular or angular blocky structure are coded 4 ;
- if the subsoil structure grade remains moderate or strong, or the texture remains coarser than silty clay loam, the code is 3.

The procedure for evaluating the K-factor with the use of the nomograph (Figure 4) is as follows:

1) Enter the nomograph on the vertical scale at the left with the appropriate percentage silt + very fine sand (0.002 mm - 0.10 mm).

2) Proceed horizontally to intersect the correct percent-sand curve (0.10 mm - 2.0 mm), interpolating to the nearest percent.

3) Proceed vertically to the correct organic matter content.

4) Proceed horizontally to the right.

5) For soils with a fine granular or fine crumb structure and moderate permeability the value of K can be read directly from the first-approximation of K scale on the right hand edge of the first section of the nomograph (only in metric units).

6) For all other soils: continue horizontally to intersect the correct structure curve.

7) Proceed vertically to the correct permeability curve.

8) Proceed horizontally to the soil-erodibility scale on the left hand edge of the second section of the nomograph to read the value of K.

1/ The classification given here is slightly different from the one given by Wischmeier et al. (9): it is taken from the Soil Survey Manual (5) pp. 167, 168.

Experience with the nomograph in the U.S.A. led to the following additional recommendations (4):

1) For soils having organic matter in excess of 4 percent, do not extrapolate; use the 4 percent curve.

2) K-values derived from the nomograph range from 0.03 (0.02 in pfs units) to 1.10 (0.69 in pfs units). For practical purposes it suffices to use K-value classes, namely: 0.13 ; 0.19 ; 0.22 ; 0.26 ; 0.31 ; 0.36 ; 0.41 ; 0.48 ; 0.56 ; 0.63 ; 0.71 ; 0.83. 1/

3) K-values must be adjusted for coarse fragments if present. K-values for soils high in coarse fragments (gravelly, channery, shaly, slaty, cherty, cobbly, stony, or flaggy 2/ are reduced y one or two classes. K-values for soils that are very high in these coarse fragments are reduced by two or three classes.

2.4 Slope length factor L and slope gradient factor S

Slope length is defined as "The distance from the point of origin of overland flow to either of the following, whichever is limiting for the major part of the area under consideration: (i) the point where the slope decreases to the extent that deposition begins, or (ii) the point where runoff enters a well defined channel that may be part of a drainage network or a constructed channel such as a terrace of diversion".

The slope length factor L is defined as:

$$L = \left(\frac{\lambda}{22.1}\right)^m \quad \ldots\ldots\ldots\ldots \quad [6,M] \quad \text{or}$$

$$L = \left(\frac{\lambda}{72.6}\right)^m \quad \ldots\ldots\ldots\ldots \quad [6, pfs] \quad \text{in which}$$

λ = field slope length (metres, feet)

m = exponent, influenced by the interaction of slope length with gradient and may be influenced also by soil properties, type of vegetation, etc.

The exponent value ranges from 0.3 for very long slopes with a gradient of less than 0.5% to 0.6 for slopes over 10%. The average value, applicable to most cases is 0.5, the value used for the development of the slope-effect chart (Figure 6). The slope-effect chart allows one to read a value for the combined effect of slope length and slope gradient. Figure 5 allows one to use this chart in cases where values for the exponent other than 0.5 are more appropriate. The figure translates the field slope length for slopes with exponents m = 0.3, m = 0.4 and m = 0.6 into equivalent slope length with exponent m = 0.5.

The slope gradient factor S is defined as:

$$S = \frac{0.43 + 0.30s + 0.043\,s^2}{6.613} \quad \ldots\ldots\ldots\ldots \quad [7] \quad \text{in which}$$

s = slope gradient (in %)

1/ In pfs units: 0.10 ; 0.15 ; 0.17 ; 0.20 ; 0.24 ; 0.28 ; 0.32 ; 0.37 ; 0.43 ; 0.49 ; 0.55 ; 0.64.

2/ For the definitions see USDA Soil Survey Manual (5), pp 215, 216.

The combined effect for slope length and slope gradient can be read from Figure 6, or can be calculated according to:

$$LS = \sqrt{\lambda}\ (0.0138 + 0.00965s + 0.00138s^2) \quad \ldots\ldots \quad [8, M], \text{ or}$$

$$LS = \sqrt{\lambda}\ (0.0076 + 0.0053s + 0.00076s^2) \quad \ldots\ldots \quad [8, pfs],$$

for slopes up to 20% and 350 m (1 148 ft) long. For slopes from 10% up to 50% and up to 800 m (2 625 ft) long, a rough estimation may be obtained from Figure 7, which has been calculated according to:

$$LS = \left(\frac{\lambda}{22.1}\right)^{0.6} \times \left(\frac{s}{9}\right)^{1.4} \quad \ldots\ldots \quad [9, M], \text{ or}$$

$$LS = \left(\frac{\lambda}{72.6}\right)^{0.6} \times \left(\frac{s}{9}\right)^{1.4} \quad \ldots\ldots \quad [9, pfs] \qquad 1/$$

Caution: Formula 9 and Figure 7 have not been sufficiently tested to indicate the reliability of the prediction.

For both Figure 6, as well as for formula [8], the field slope length λ should be substituted by the equivalent slope length whenever $M \neq 0.5$.

Equations [6], [7], [8] and [9] apply only to uniform slopes with one type of soil or one type of cover over the total length.

If significant changes occur in a) slope gradient, b) slope form (convex, straight, concave), c) soil type, or d) soil cover, corrections need to be made (8).

Depending on the complexity of the situation, two procedures can be followed to arrive at the appropriate average values for the total slope. The procedures as given take only a change of slope gradient into account. However, it is possible to use the same procedures to also evaluate changes in soil type and/or soil cover as will be illustrated at the end of this section.

Procedures

If two simplifying assumptions can be accepted, the adjustments are rather easy. The assumptions are: (i) the change in gradient is not sufficient to cause upslope deposition, and (ii) the irregular slope can be divided into a small number of equal-length segments.

The adjustment procedure, if both assumptions are accepted, is as follows (8):

1) Divide the slope into the necessary equal-length segments and determine the slope gradient factor value (S), according to equation [7] for each segment.

2) Multiply the obtained S-value by the slope length factor value (L), according to equation [6], using the total slope length.

3) Multiply each of the obtained LS-values by adjustment factor a. Adjustment factor a can be read from Table 2 for slopes with a slope-length exponent M = 0.5 or otherwise be calculated by:

1/ Adapted from SCS (3)

$$a = \left[j^{(m+1)} - (j-1)^{m+1} \right] / n^m \qquad [10]$$

in which:

a = adjustment factor

j = sequence number of segment (from top to bottom)

m = slope length exponent

n = total number of equal-length segments

4) Average the adjusted LS-values to obtain the effective LS-value for the total slope.

Table 2: Adjustment Factor: a for Correction of the LS Chart Values for Successive Segments of a Slope where the Slope-length Exponent Equals 0.5

Segment No. (Top to Bottom)	Total Number of Equal-length Segments			
	2	3	4	5
1	0.71	0.58	0.50	0.45
2	1.29	1.06	0.91	0.82
3		1.37	1.18	1.06
4			1.40	1.25
5				1.42

(This table appeared originally in Wischmeier (8), p. 181)

If it is not possible to divide the slope into equal-length segments, a different procedure must be followed, as follows:

1) Determine the value of the term u. For slopes with a slope-length exponent of m = 0.5 the value of U can be read from the nomograph developed by Forster and Wischmeier (1), which is given as Figure 8. For slopes with a slope-length exponent of $m \neq 0.5$ the value of u can be calculated according to:

$$u = S\lambda^{(m+1)} / 22.1^m \quad \ldots\ldots\ldots \quad [11, M], \text{ or}$$

$$u = S\lambda^{(m+1)} / 72.6^m \quad \ldots\ldots\ldots \quad [11, pfs]$$

in which:

u = term defined by equation [11]

S = slope gradient factor value (calculated according to equation [7])

λ = slope length (metres, feet)

m = slope-length exponent

Using the nomograph (1):

a) enter the nomograph on the horizontal axis with the value of $\lambda_{(j-1)}$ 1/

b) move upward to the curve for the percent slope for segment j

c) read the value of u_{1j} on the vertical scale

d) enter the nomograph on the horizontal axis with the value of λ_j to obtain the corresponding value of u_{2j}

2) Calculate the effective LS-value according to:

$$LS = \left[\sum_{j=1}^{n} (u_{2j} - u_{1j}) \right] \bigg/ \lambda_e \quad \ldots\ldots\ldots \quad [12]$$

in which:

j = sequence number of segment (from top to bottom)

n = total number of segments

u_{1j} = value of u for upper limit of segment j (metres, feet)

u_{2j} = value of u for lower limit of segment j (metres, feet)

λ_e = entire slope length (metres, feet)

If changes in soil type and/or soil cover occur and the first procedure is followed, the values obtained after step 3 has been concluded are multiplied with the K and/or C and/or P factor values pertinent to each segment, then the adjusted values are averaged to obtain the pertinent value for the total slope.

In case the second procedure is followed, equation [12] becomes:

$$KLSCP = \left[\sum_{j=1}^{n} K_j C_j P_j (u_{2j} - u_{1j}) \right] \bigg/ \lambda_e$$

in which:

K_j = value of K-factor for section j

C_j = value of C-factor for section j

P_j = value of P-factor for section j

2.5 Cropping management factor: C

This factor describes the total effect of vegetation, residue, soil surface and management on soil loss. The value of the factor is in most cases not constant over the year. Although treated as an independent variable in the equation, the "true" value of this factor is probably dependent upon all other factors. Therefore, the value of the C-factor needs to be established experimentally in many cases.

1/ $\lambda_{(j-1)}$ is the distance from the summit to the bottom of segment (j-1); so $\lambda_{(j=n)}$ equals λ_e.

For crops: C-values need to be established for each of the following stages for all crops of the rotation (11):

period F: rough fallow (turn ploughing to seeding);

period 1: seeding (seedbed preparation to 1 month after planting);

period 2: establishment (from 1 to 2 months after spring or summer seeding; for fall seeded grain this period includes the winter months);

period 3: growing and maturing crops from the end of period 2 to crop harvest;

period 4: residue or stubble.

Caution: The value found for a period F in the rotation cannot be extrapolated to any other fallow periods within the rotation, because the value is influenced by the cropping history of the soil, the nature and quantity of residue turned under and other factors.

In order to arrive at a proper value for a crop rotation the soil loss ratio (i.e. the ratio of soil loss from the field with the particular cropping and management to that of bare soil) has to be adjusted according to the distribution of the erosion-index for each period, because field conditions are immaterial when there is no rain and most important when there is much rain. Therefore the soil loss ratio for each period is multiplied with the percentage of EI_{30}-index applicable to that period. This percentage of EI_{30}-index can easily be read from an erosion-index distribution curve (see Figure 3). For the U.S.A. east of the Rocky Mountains tables have been developed from which the soil loss ratios for the different periods of the common rotations can be read. In combination with the appropriate erosion-index distribution curve, the C-value for any part of the rotation can be established. This table and the distribution curves are presented in Agriculture Handbook No. 282 (11).

In areas of the world for which no guidelines for the establishment of C-values for field-crops exist, it is probably easiest to try to correlate soil loss ratio with amount of dry organic matter per unit area or with percent ground cover.

For permanent pasture, range lands and idle lands and for woodlands, tables have been published (3) from which the average annual C-values can be read. These tables are reproduced as Table 3 and Table 4.

Caution: When applied outside the U.S.A. the values may need to be adapted to local conditions and should be tested locally.

2.6 Erosion-control practice factor: P

The effect of erosion-control measures is thought to be an independent variable, therefore it has not been included in the cropping management factor. The soil loss ratios for erosion-control practices vary according to slope gradient. Soil loss ratios for contouring, contour strip cropping and terracing are given in Table 5. In Table 5, two values are presented for terracing: the higher one describes the soil loss from the field, the lower one the effect on sediment yield, the difference being the sediment lost from the field but trapped in the terrace channel.

TABLE 3: "C" Values for Permanent Pasture, Rangeland, and Idle Land[a]

Vegetal Canopy			Cover That Contacts the Surface					
Type and Height of Raised Canopy[b]	Canopy Cover[c] %	Type[d]	Percent Ground Cover 0	20	40	60	80	95-100
Column No.:	2	3	4	5	6	7	8	9
No appreciable canopy		G	.45	.20	.10	.042	.013	.003
		W	.45	.24	.15	.090	.043	.011
Canopy of tall weeds or short brush (0.5 m fall ht.)	25	G	.36	.17	.09	.038	.012	.003
		W	.36	.20	.13	.082	.041	.011
	50	G	.26	.13	.07	.035	.012	.003
		W	.26	.16	.11	.075	.039	.011
	75	G	.17	.10	.06	.031	.011	.003
		W	.17	.12	.09	.067	.038	.011
Appreciable brush or bushes (2 m fall ht.)	25	G	.40	.18	.09	.040	.013	.003
		W	.40	.22	.14	.085	.042	.011
	50	G	.34	.16	.085	.038	.012	.003
		W	.34	.19	.13	.081	.041	.011
	75	G	.28	.14	.08	.036	.012	.003
		W	.28	.17	.12	.077	.040	.011
Trees but no appreciable low brush (4 m fall ht.)	25	G	.42	.19	.10	.041	.013	.003
		W	.42	.23	.14	.087	.042	.011
	50	G	.39	.18	.09	.040	.013	.003
		W	.39	.21	.14	.085	.042	.011
	75	G	.36	.17	.09	.039	.012	.003
		W	.36	.20	.13	.083	.041	.011

a/ All values shown assume: (1) random distribution of mulch or vegetation, and (2) mulch of appreciable depth where it exists.

b/ Average fall height of waterdrops from canopy to soil surface: m = meters.

c/ Portion of total-area surface that would be hidden from view by canopy in a vertical projection, (a bird's-eye view).

d/ G: Cover at surface is grass, grasslike plants, decaying compacted duff, or litter at least 5cm (2 inches) deep.

W: Cover at surface is mostly broadleaf herbaceous plants (as weeds) with little lateral-root network near the surface, and/or undecayed residue.

(This Table appeared as Table 1 in SCS (3), p. 2).

Table 4 - "C" Factors for Woodland
(This Table appeared as Table 2 in SCS (3), p.3)

Stand Condition	Tree Canopy a/ % of Area	Forest Litter b/ % of Area	Undergrowth c/	"C" Factor
Well stocked	100-75	100-90	Managed d/ Unmanaged d/	.001 .003-011
Medium stocked	70-40	85-75	Managed Unmanaged	.002-.004 .01-.04
Poorly stocked	35-20	70-40	Managed Unmanaged	.003-.009 .02-.09 e/

a/ When tree canopy is less than 20%, the area will be considered as grassland, or cropland for estimating soil loss. See Table 3.

b/ Forest litter is assumed to be at least two inches deep over the percent ground surface area covered.

c/ Undergrowth is defined as shrubs, weeds, grasses, vines, etc. on the surface area not protected by forest litter. Usually found under canopy openings.

d/ Managed - grazing and fires are controlled.
Unmanaged - stands that are overgrazed or subjected to repeated burning.

e/ For unmanaged woodland with litter cover of less than 40%, C values should be taken from table 3.

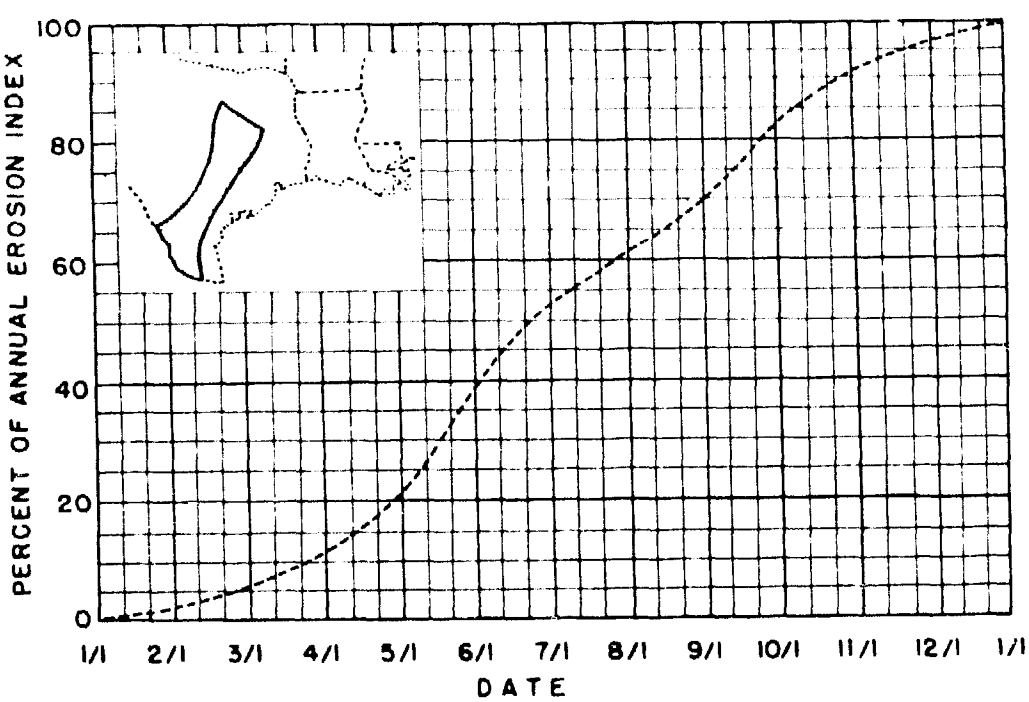

Figure 3. Erosion index distribution curve for part of Texas as noted in inset. (Reproduced from Wischmeier and Smith (11), Fig. 9, curve 10, p. 22).

TABLE 5: "P" Factors for Contouring, Contour Stripcropping and Terracing

Land Slope	P Values			
%	Contouring	Contour Stripcropping	Terracing a/	Terracing b/
2.0 to 7	0.50	0.25	0.50	0.10
8.0 to 12	0.60	0.30	0.60	0.12
13.0 to 18	0.80	0.40	0.80	0.16
19.0 to 24	0.90	0.45	0.90	0.18

a/ For erosion-control planning on farmland.

b/ For prediction of contribution to off-field sediment load.

(This Table appeared in SCS (3), p. 9).

TABLE 6: Guide for Assigning Soil Loss Tolerance Values (T) to Soils Having Different Rooting Depths

Rooting Depth	Soil Loss Tolerance Values Annual Soil Loss - Tons/ha (Tons/acre)	
cm (inches)	Renewable Soil a/	Non-Renewable Soil b/
0 - 25 (0-10)	2.2 (1)	2.2 (1)
25 - 50 (10-20)	4.5 (2)	2.2 (1)
50 - 100 (20-40)	6.7 (3)	4.5 (2)
100 - 150 (40-60)	9.0 (4)	6.7 (3)
150 (60)	11.2 (5)	11.2 (5)

a/ Soils with favourable substrata that can be renewed by tillage, fertilizer, organic matter, and other management practices.

b/ Soils with unfavourable substrata such as rock or soft rock that can not be renewed by economical means.

(This Table appeared in SCS (4), p. 4).

3. APPLICATIONS OF THE USLE

3.1 Predicting annual or rotational field soil loss

In order to predict soil loss the annual (or rotational) EI_{30}-value, the K-value, the LS-value, the annual (or rotational) C-value, and the P-value are evaluated and equation [1] is solved.

3.2 Predicting field soil loss with X-year return period

The procedure to be followed is essentially the same as that for predicting average annual soil loss, with one exception: instead of the annual EI_{30}-value, the EI_{30}-value with an X-year return period needs to be calculated.

3.3 Predicting individual storm field loss

Because the relations used in the USLE represent statistical averages, predictions of **individual storm losses are less accurate. However, valuable estimates can be obtained** if the EI_{30}-value of the individual storm is known and if the C-value for the actual field conditions during the storm can be established.

3.4 Aid to conservation planning

For conservation planning the soil loss tolerance(T)(i.e., the maximum soil loss that can be tolerated) needs to be established. The following guidelines are used in the U.S.A. (quoted from SCS) (4).

Soil loss tolerance (T), sometimes called permissible soil loss, is the maximum rate of soil erosion that will permit a high level of crop productivity to be sustained economically and indefinitely.

Soil loss tolerance values (T) of 2.3 through 11.2 are used. The numbers represent the permissible tons of soil loss per ha per year 1/ where food, feed and fiber plants are to be grown. "T" values are not applicable to construction sites or to other non-farm uses of the erosion equation.

A single T value is normally assigned to each soil series. A second T-value may be assigned to certain kinds of soil where erosion has significantly reduced the thickness of the effective root zone; thus reducing the potential of the soil to produce plants over an extended period of time. For example, eroded phases of soil series that are shallow to moderately deep to a soil layer that restricts roots are commonly given a T-value one class lower than the uneroded phase of the same soil. The following criteria are used by soil scientists and other specialists for assigning soil loss tolerance values (T) to soil series:

1) An adequate rooting depth must be maintained in the soil for plant growth. For soils that are shallow over hard rock or other restrictive layers, it is important to retain the remaining soil; therefore, not much soil loss is tolerated. The soil loss tolerance should be less on soils shallow to impervious layers than for soils with good soil depth or for soils with favourable underlying soil materials that can be renewed by management practices.

2) Soils that have significant yield reductions when the surface layer is removed by erosion are given lower soil loss tolerance values than those where erosion effects yield very little.

1/ 1 to 5 tons/acre per year

A maximum of 11.2 tons of soil loss per ha per year has been selected for use with the universal soil loss equation. This maximum value has been used for the following reasons:

1) Soil losses in excess of 11.2 tons per ha per year affect the maintenance, cost and effectiveness of water-control structures such as open ditches, ponds, and other structures affected by sediment.

2) Excessive sheet erosion is accompanied by gully formation in many places causing added problems to tillage operations and to sedimentation of ditches, streams and waterways.

3) Loss of plant nutrients. The average value of nitrogen and phosphorus in a ton of soil is about $2-$3. Plant nutrient losses of more than $25 per ha per year is considered to be excessive. 1/

4) Numerous practices are known that can be used successfully to keep soil losses below 12.5 tons per ha per year.

The accompanying guide is given as Table 6.

After having established the soil loss tolerance we can rewrite [1] as:

$$CP = T/RKLS \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad [12]$$

By choosing the right cropping management system and appropriate conservation practices, a value for the combined effect of C and P can be established that fits equation [12]. In order to do so it will be helpful to consult the erosion-index distribution curve of the area in order to single out the most critical stages as far as rainfall agressivity is concerned, because these are the stages where improvements result in the greatest reduction in the C-value.

3.5 Watershed management planning to reduce erosion (an example)

The following section is reproduced from SCS (3).

Assume a watershed area of 243 ha (600 acres) above a proposed floodwater retarding structure in Fountain County, Indiana. Compute the average annual soil loss from sheet erosion for present conditions and for future conditions after recommended land treatment is applied on all land in the watershed.

Present Conditions

Cropland - 113.3 ha (280 acres)
Continuous corn with residue removed - average yield - 4.4 tons/ha (70 bu/acre)
Cultivated up and down slope
Soil - Fayette silt loam
Slope - 8 percent
Slope length - 61.0 m (200 ft)

R = 321 (185)
K = .48 (.37)
LS = 1.4
C = .43
P = 1.00

A = 321 x .48 x 1.4 x .43 x 1.0 = 92.8 metric tons/ha/year (41.2 (short) tons/acre/year) soil loss.

1/ Monetary values are estimates from 1973.

Pasture - 68.8 ha (170 acres)
Canopy or short brush - 0.5 m fall height
Percent cover provided by canopy - 50%
Surface cover - grass and grasslike plants
Percent of surface or ground cover - 80%
Soil - Fayette silt loam
Slope - 8 percent
Slope length - 61.0 m (200 ft)

R = 321 (185)
K = .48 (.37)
LS = 1.4
C = .012

A = 321 x .48 x 1.4 x .012 = 2.6 metric tons/ha/year (1.15 (short) tons/acre/year)

Forest - 60.7 ha (150 acres)
Percent of area covered by tree canopy - 30%
Percent of area covered by litter - 50%
Undergrowth - unmanaged
Soil - Bates silt loam
Slope - 12 percent
Slope length - 30.5 m (100 ft)

R = 321 (185)
K = .41 (.32)
LS = 1.8
C = .05

A = 321 x .41 x 1.8 x .05 = 11.9 metric tons/ha/year (5.3 (short) tons/acre/year)

Future Conditions

Cropland - 113.3 ha (280 acres)
Rotation of wheat, meadow, corn, corn with residue left
Contour stripcropped
Soil - Fayette silt loam
Slope - 8 percent
Slope length - 61.0 m (200 ft)

R = 321 (185)
K = .48 (.37)
LS = 1.4
C = .119
P = .3

A = 321 x .48 x 1.4 x .119 x .3 = 7.7 metric tons/ha/year (3.4 (short) tons/acre/year)

Pasture - 68.8 ha (170 acres)
With improved management:
Canopy cover decreased to 25 percent with 4 m fall height
Ground cover increased to 95 percent (for area not protected by canopy)
Soil - Fayette silt loam
Slope - 8 percent
Slope length - 61.0 m (200 ft)

R = 321 (185)
K = .48 (.37)
LS = 1.4
C = .003

A = 321 x .48 x 1.4 x .003 = 0.65 metric tons/ha/year (0.29 (short) tons/acre/year)

Forest - 60.7 ha (150 acres)
With improved management:
Canopy cover increased to 60 percent
Litter cover increased to 80 percent
Undergrowth - managed
Soil - Bates silt loam
Slope - 12 percent
Slope length - 30.5 m (100 ft)

R = 321 (185)
K = .41 (.32)
LS = 1.8
C = .003

A = 321 x .41 x 1.8 x .003 = 0.71 metric tons/ha/year (0.32 (short) tons/acre/year)

Summary of Average Annual Soil Losses (in SI-units only)

Present Conditions

Cropland	-	113.3 ha	x	92.8 tons/ha	=	10 514 tons/year
Pasture	-	68.8 ha	x	2.6 tons/ha	=	179 tons/year
Forest	-	60.7 ha	x	11.9 tons/ha	=	722 tons/year

Future Conditions

Cropland	-	113.3 ha	x	7.7 tons/ha	=	872 tons/year
Pasture	-	68.8 ha	x	.65 tons/ha	=	45 tons/year
Forest	-	60.7 ha	x	.71 tons/ha	=	43 tons/year

Remember that the erosion from a catchment is not directly comparable to the amount of sedimentation of reservoirs downstream. The average annual soil loss, as calculated in the example here, is the gross erosion taking place. The amount of this material which is transported by streams depends on the sediment delivery ratio (i.e., the ratio of sediment delivered into a reservoir to gross erosion). Finally, only a portion of this transported sediment is trapped in a reservoir, depending on a reservoir's trap efficiency. The paper by Dunne in this series briefly discusses sediment delivery ratios and trap efficiency, giving some further references. A good summary also is found in Technical Release No. 22 (geology), August 1964 by the Engineering Division of the U.S. Soil Conservation Service entitled "Reservoir sedimentation surveys". Another good reference is "Design of small dams" 1973, U.S. Bureau of Reclamation, U.S. Government Printing Office, 816 pages, Denver Federal Centre, Denver, Colorado, U.S.A. 80225 ($12.65).

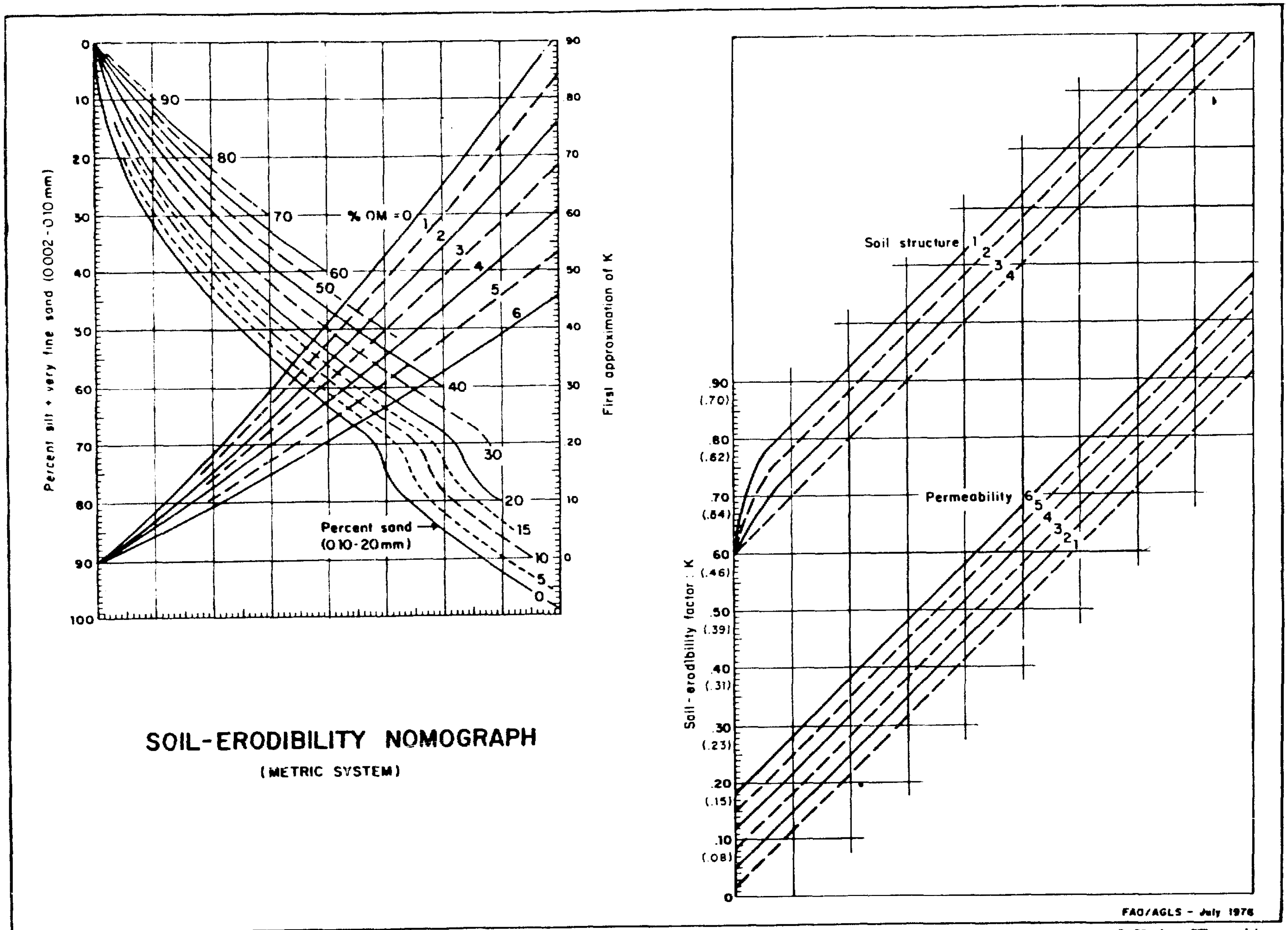

Figure 4. Soil erodibility nomograph. For codification and procedure see text. First approximation of K in SI-units only; final result of soil erodibility factor, K both in SI-units and pfs-units, with the latter in brackets. (Adapted from Wischmeier et al (9), Figure 1, p. 190).

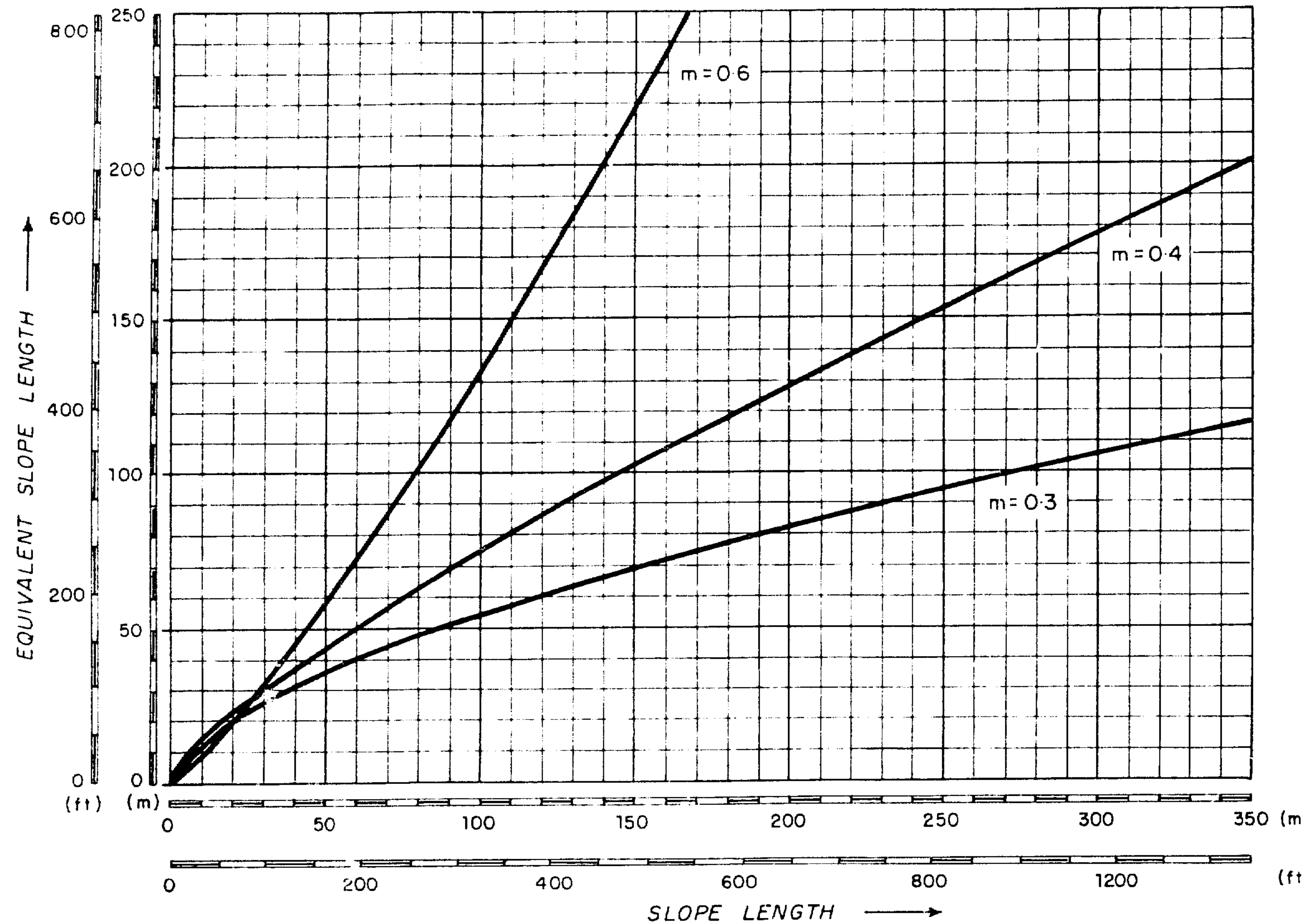

Figure 5. Equivalent slope lengths for use of slope-effect chart when the value of the pertinent slope length-exponent m is not 0.5. (Adapted from Wischmeier and Smith (11), Figure 3, p. 9). Note in the text also that λ = slope length (i.e., actual length on the ground).

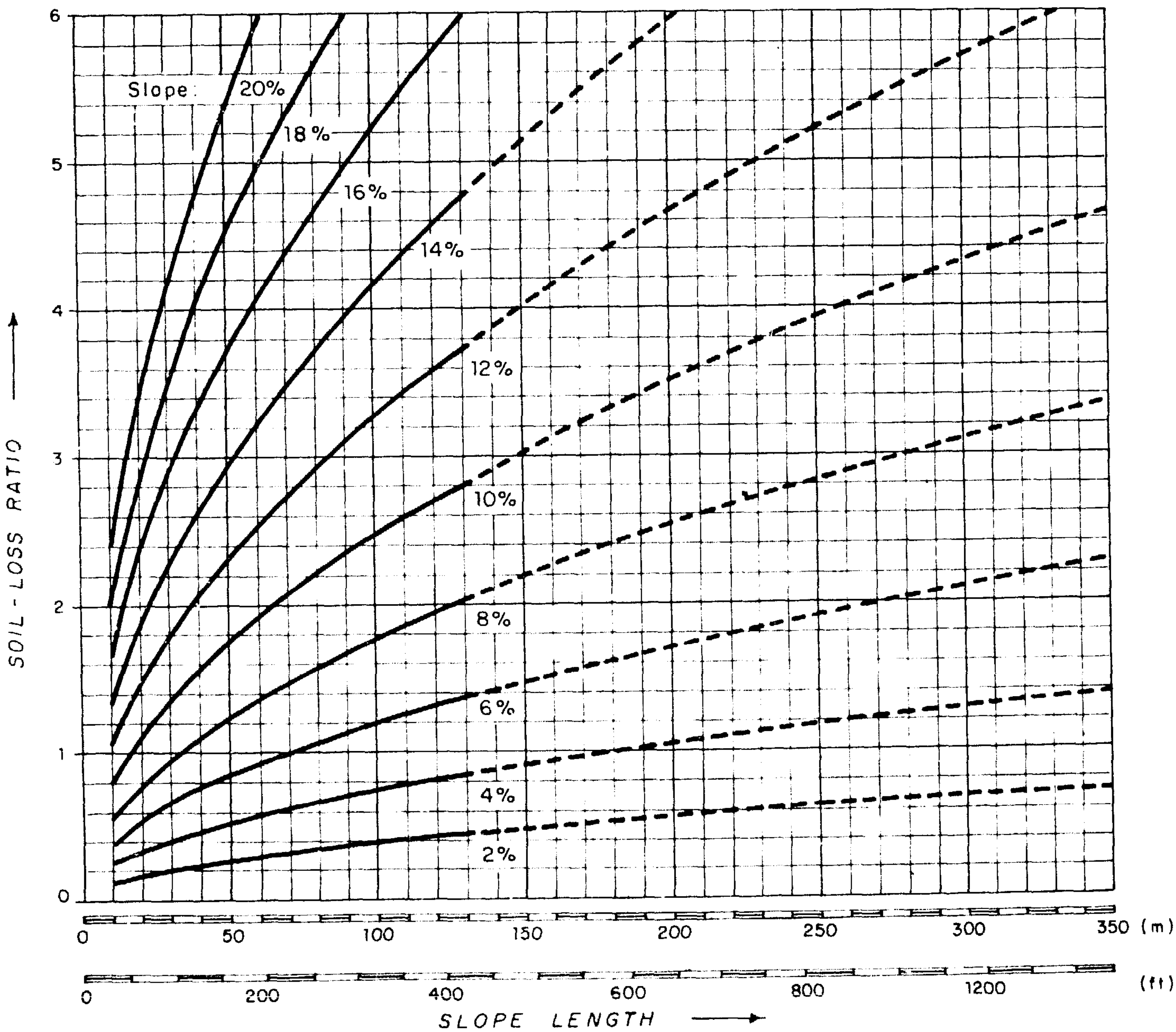

Figure 6. Slope-effect chart showing the combined effect of slope length λ and slope gradient S. (Adapted from Wischmeier and Smith (11), Figure 2, p. 8).

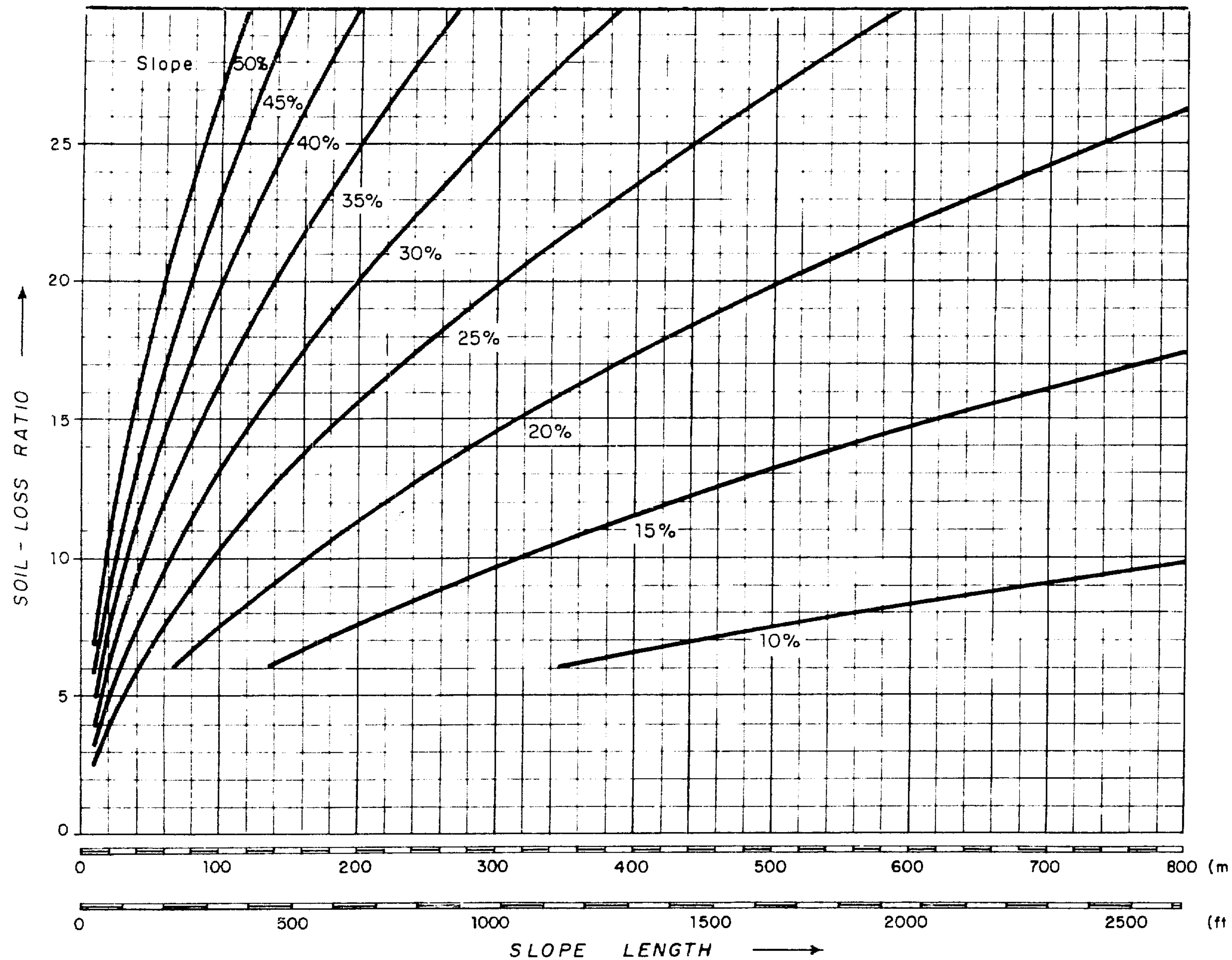

Figure 7. Slope-effect chart for slope lengths λ and slope gradients S exceeding those in Figure 6. Extrapolated beyond the range of the data; use only as speculative estimates. (Adapted from SCS (3), Figure 3, p. 8).

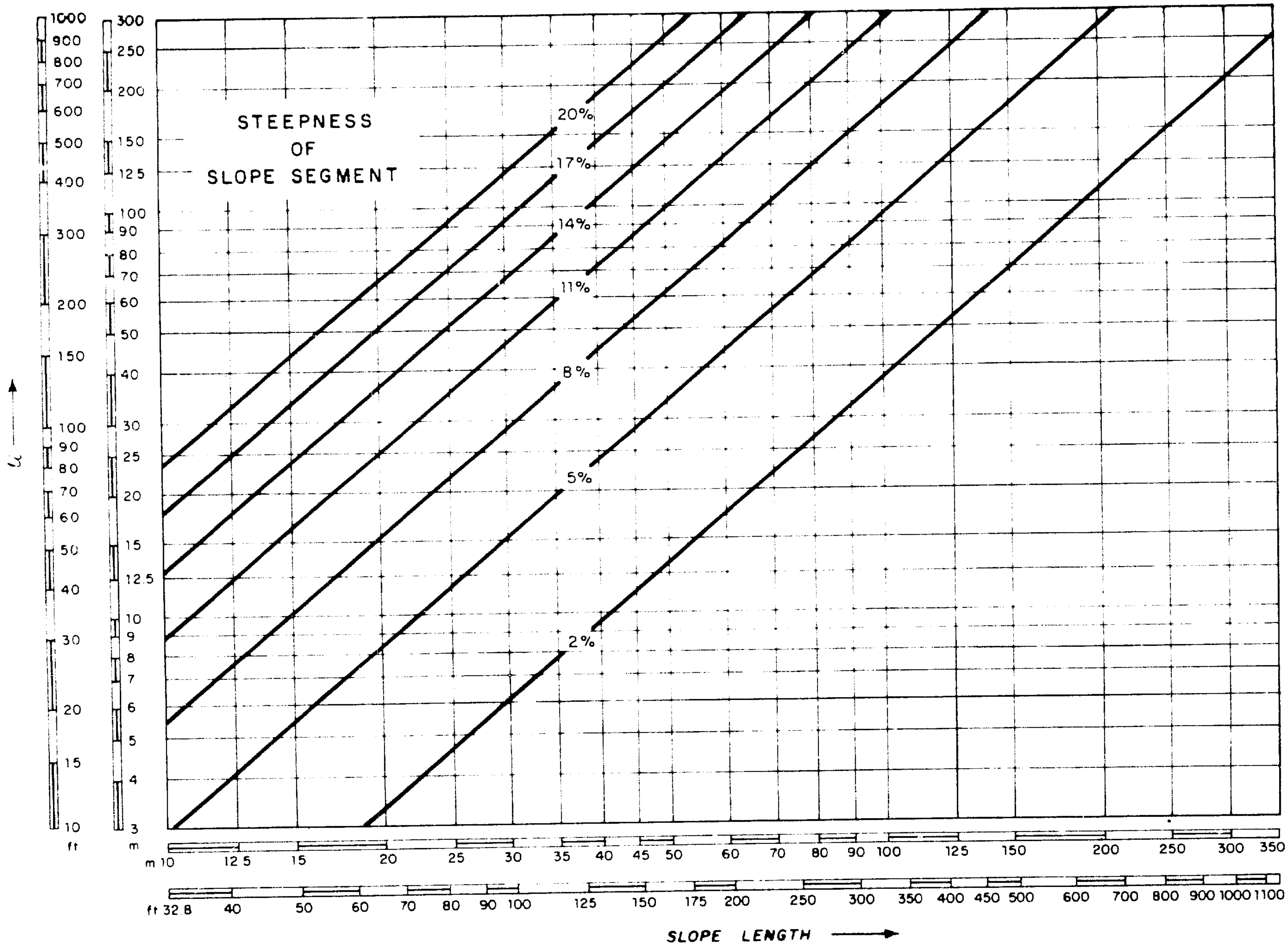

Figure 8. Chart for computing $u = S^{1.5} / 22.1^{0.5}$ (or $u = S^{1.5} / 72.6^{0.5}$ in pfs), where S = slope factor and λ = distance from top of slope to lower edge of segment. (Adapted from Forster and Wischmeier (1), Figure 2, p. 307).

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1/ Technical Release No. 51 has been revised and reissued as Technical Release No. 51 (Rev.) in January 1975.

IX.

PROCEDURE FOR DETERMINING RATES OF LAND DAMAGE, LAND DEPRECIATION AND VOLUME OF SEDIMENT PRODUCED BY GULLY EROSION [1/]

by

U.S. Department of Agriculture
Soil Conservation Service
Engineering Division

1. GENERAL

This technical release provides a guide to the determination of future rates of potential land damage, land depreciation and sediment produced by gully erosion. The term "gully", as used in this guide, includes upland and valley side-wall gullies as well as incising channels within flood plains commonly called valley trenches. Justification of structural measures for gully stabilization is based on a reduction of expected future damages.

The procedure here illustrates a method of predicting gully erosion and is therefore a step toward predicting sediment from local, gully areas and for establishing rehabilitation priorities.

The method presented is acceptable for adjusting the historical rate of growth to the probable future rate on the basis of measurable conditions above an advancing headcut. Each of the primary factors influencing the rate of gully erosion is considered and incorporated to the extent possible in this procedure. Where quantitative values are not assigned to specific factors, criteria are provided to aid in selecting proper values. The procedures set forth here are the minimum technical standards for SCS work to be used to predict the future rate of development of an existing gully and to estimate the area of land eroded and the location and area of land depreciated.

This method was developed with reference to areas east of the Rocky Mountains in USA, the narrow belt along the Pacific Coast, and for higher mountainous areas in the western USA. For more arid areas, (i.e., less than about 500 mm), a variation in procedure is required. Many of the principles here are, nonetheless, common to both humid and arid zones.

2. NATURE OF DAMAGE RESULTING FROM GULLY EROSION

2.1 Land Damage

Land damage by gully erosion is a permanent, largely non-recoverable damage. Land damage is physically expressed by the geologist in terms of the area eroded by a gully or gully system.

1/ This manuscript was issued originally as "Technical Release No. 32 (Geology), July, 1966, by the SCS. Reproduced here with permission of SCS with minor revisions and added comments for the purpose of this FAO publication.

2.2 Land Depreciation

Land depreciation is the loss of net income due to a lower level of production and pattern of land use associated with gully erosion. Land depreciation occurs on physically undamaged land adjacent to, or influenced by, a gully. (Note: such an example is the lowering of groundwater tables, because of deep gullies, which affects areas around the gully, as in the gullied "dambo" areas of Africa).

2.3 Sediment Damage

Sediment damage is damage which occurs to downstream enterprises by deposition of sediment or sediment in transport. Examples of sediment damage are deposits on land, streets and roads; swamping; deposition in reservoirs and channels; and increased water filtration costs.

3. CONDITIONS INFLUENCING GULLY EROSION

Gully development is initiated as a result of changes in conditions which influence the hydraulic characteristics of flow or the forces that resist erosive flows. Once the gully channel is established, the resulting concentration of flow is sufficient to sustain gully erosion. Subsequent headward erosion and widening will continue until the gully is adjusted to a new set of equilibrium conditions and becomes relatively stable.

In general, the annual rate of gully advance is variable, being more rapid at some stages in its life cycle than in others. Observations indicate that the rate of advancement progressively decreases in the final stages of development. The factors that influence the rate of gully advancement at any period in its life history are varied and complex. Our knowledge of the relative importance of the causal factors has not progressed to the extent that precise quantitative values can be placed on all of the variables believed to be significant in gully erosion. Consequently, adequate prediction of the rate of advancement depends largely upon the experience and judgment of the geologist in recognizing controlling factors and assigning proper quantitative values to those factors which have not yet been statistically evaluated.

Experience has shown that the prediction of the future rate of gully advancement, based on the historical rate alone, can lead to serious errors of prediction and evaluation unless proper consideration is given to those factors which may have a major influence on the rate of advancement. Condition factors such as the characteristics of the geologic materials, topography, land use, and volume of run-off control the rate of gully advance. A change in conditions above an advancing gully head changes the rate of advancement.

The influence of these factors on the rate of headward advancement is recognized. However, in this procedure only the relationships involving area and precipitation were used. These were developed as a result of SCS field measurements on 210 gullies in six widely scattered land resource areas east of the Rocky Mountains in the United States. One of the analytical results of these studies was reported previously. 1/ The following relationship between headward advancement and the primary causal factors was found from a more recent analysis: 2/

$$R = 1.5\ (W)^{.46}(P_{0.5})^{.20}$$

1/ Thompson, J.R., 1964, "Quantitative Effect of Watershed Variables on Rate of Gully-Head Advancement" Trans. of ASAE, Vol. 7, No. 1, pp. 54-55.

2/ Data analyzed by the Statistical Reporting Service, USDA, Washington, D.C.

where

R = rate of headward advancement, in feet per year (note metric conversion, table below)

W = average drainage area above headcut, in acres

$P_{0.5}$ = the summation of 24-hour rainfalls of 0.5 inch or greater occuring during the life of the gully, converted to an average annual basis, in inches.

Conversion:

feet x 0.30 = m
ha x 2.47 = acres
mm x 0.04 = inches; i.e., 1 inch = 25.4 mm
m x 3.28 = feet

At least four other factors, not included in the foregoing measurements, are known to influence the rate of headward advancement of gullies. These are: (1) changes in erodibility of soil material through which the gully advances, (2) the slope of the approach channel above the headcut, (3) changes in run-off due to changes in land use and practices in watershed and (4) the influence of ground water. Judgement must be used in adjusting for the effect of these factors on the future rate of gully head advance as determined from the procedure given below.

With the foregoing knowledge and using the principle of proportions, it is possible to establish an equation for predicting the future rate of headward erosion, if the past rate is known and the future changes in conditions can properly be anticipated. The prediction equation is as follows:

$$R_f = R_p (A)^{.46} (P)^{.20} \qquad \text{(Equation 2)}$$

where

R_f = computed future average annual rate of gully head advance for a given reach, in feet per year (note metric conversions)

R_p = past average annual rate of gully head advance, in feet per year

A = ratio of the average drainage area of a given upstream reach (W_f) to the average drainage area of the reach through which the gully has moved (W_p) (area in acres)

P = ratio of the expected long-term average annual inches of rain from 24-hour rainfalls of 0.5 inch or greater (P_f) to the average annual inches of rain from 24-hour rainfalls of 0.5 inch or greater for the period, if less than 10 years, in which the gully head has moved (P_p)

Equation 2 should be used in estimating the future rate of development of gullies for determining, on the basis of potential future damage, the extent of expenditures which could be justified in any specific case.

Stabilization of a gully in the initial stages of development with high potential future damage can normally be economically justified. The same control measures for a gully which has practically reached its maximum stage of development normally cannot be economically justified.

Gully erosion consists of headward advance, upstream migration of secondary knickpoints, and widening of the gully channel. In computing and analyzing rates of development for projection into the future, each of these types of growth should be considered separately.

Each advancing head, whether main or lateral, should be treated independently. Also, when the drainage entering a head indicates the probability of tributary gully development, the potential development of gully heads in these tributaries should be considered and their estimated rate of growth calculated.

4. VALUES FOR FACTORS IN THE EQUATION

The parametres of the formula are described here. Examples of their use can be found in Section 5 below.

4.1 Past Rate of Gully Erosion

In the use of this procedure the past annual rate of gully advance, or the R_p value must be determined. This is the reach of existing gully indicated as reach A-B in Figure 1. The length of the gully advancement is determined by use of aerial photographs, maps, field inspection or other methods. The age is established by interview, inspection of old aerial photographs, or other means. "R_p," the average annual rate of headward advance in feet per year, is computed as follows:

$$R_p = \frac{\text{Gully length (ft.)}}{\text{Age of gully (yrs.)}} = \text{ft./yr}$$ (Note metric conversion, table above)

4.2 Adjustment for Change in Contributing Drainage Area

Analysis of a large number of gullies has shown that the rate of advance is related approximately to the square root of the drainage area.

Therefore, a series of reaches are delineated upstream from the present gully head for the purpose of estimating the effect of changing drainage areas on future rates of advance.

Each reach, depending on its drainage area, will have a different effect on the total run-off over the head. The ratios of the mean drainage areas of the reaches to the average drainage area of the reach through which the gully has moved (Reach A-B, Figure 1) are represented by the letter "A".

$$A = \frac{W_f \text{ (Drainage Area of Upstream Reach)}}{W_p \text{ (Drainage Area of Reach A-B)}}$$

$$A^{0.46} = \frac{W_f}{W_p}^{0.46}$$

$A^{0.46}$ may be read directly from Figure 2.

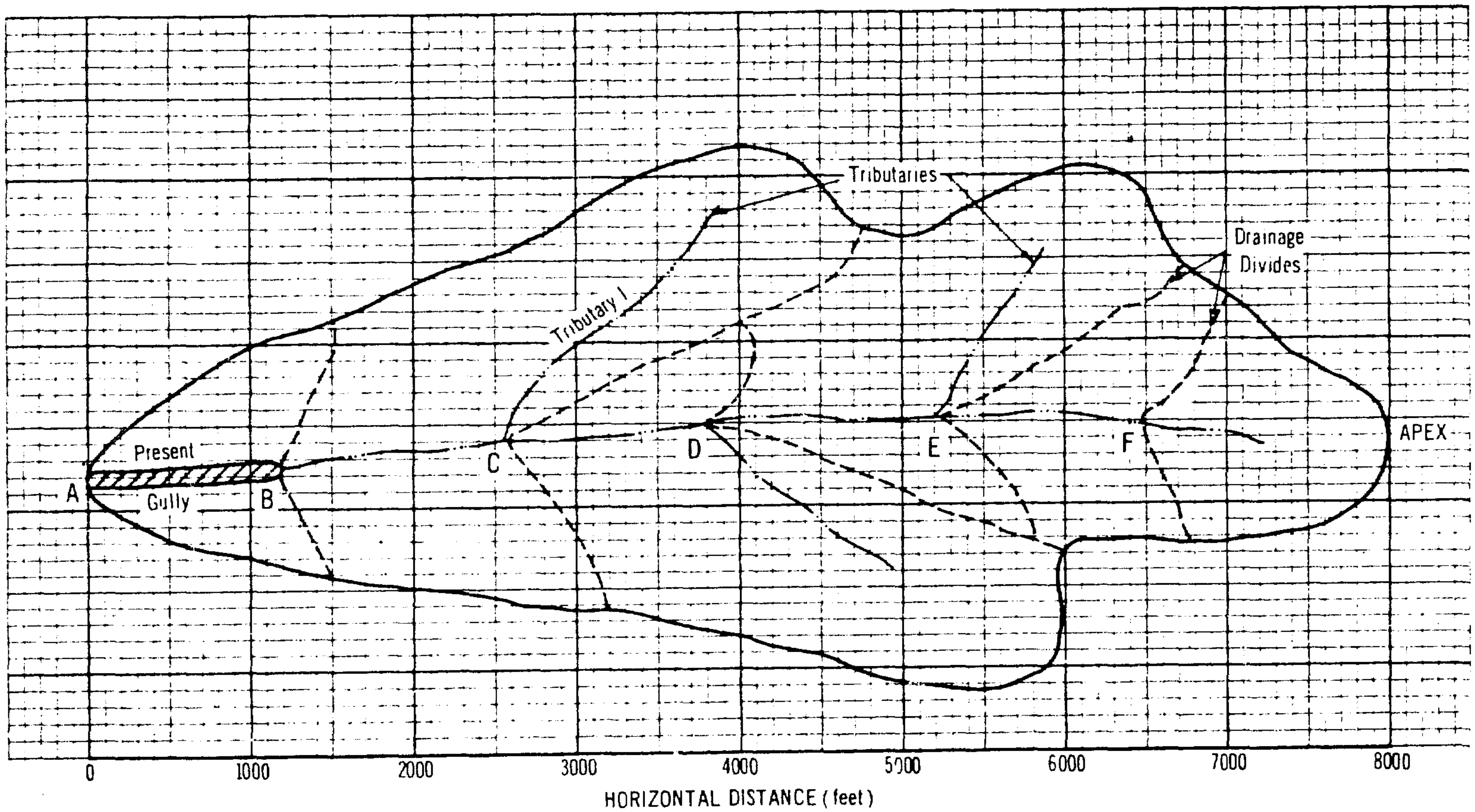

FIGURE 1 - Drainage Area of the Gully Showing the Reaches Selected, Horizontal Distance, Tributaries and Subwatersheds.
(Note: feet x 0.30 = metres)

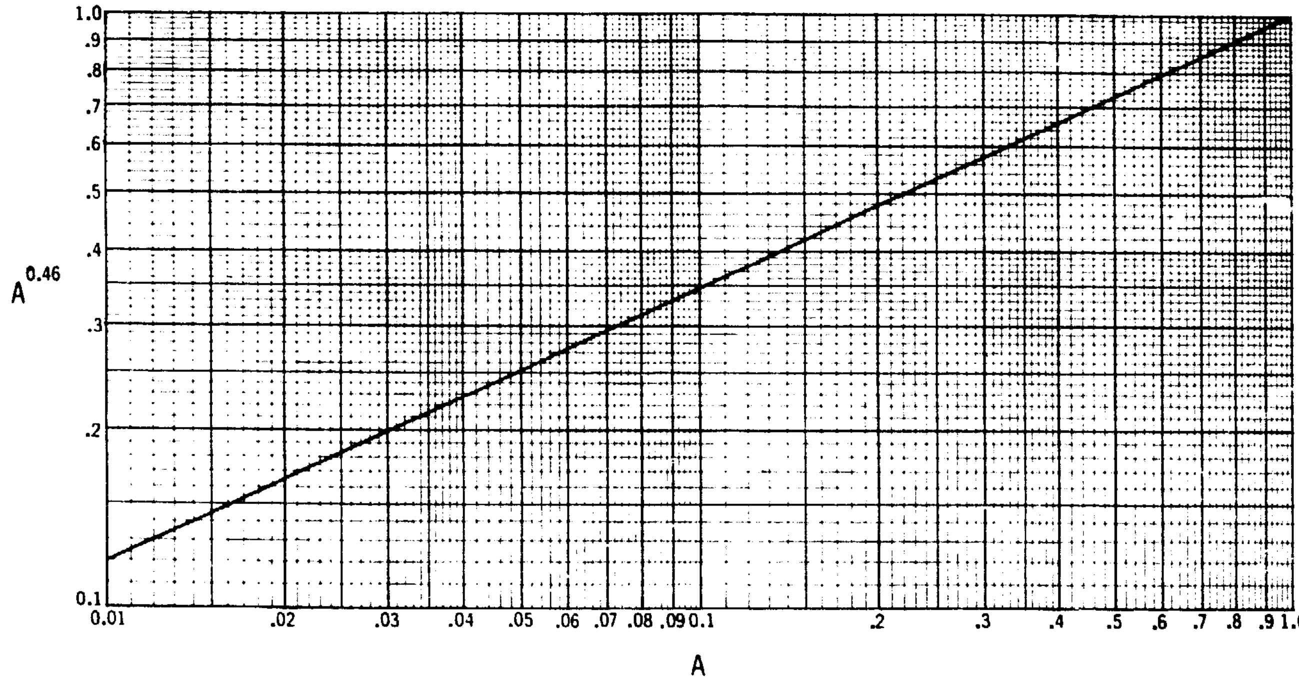

Figure 2. Graph for Obtaining the 0.46 Power of Ratio A (for adjustment for drainage area size changes due to gully advance)

4.3 Adjustment for Precipitation

The precipitation factor is a ratio that relates the expected future long-term average precipitation with the average annual precipitation that occurred during the advance of the present gully. The average annual rainfall of 24-hour rainfalls of 0.5 inch or greater for the past period of advance of the existing gully may be computed from climatological data. 1/ (Note 0.5 inch = 13 mm).

This procedure should be done only if the age of the gully is less than 10 years, particularly if recent years were not "average", for example a droughty period. The value for the expected future long-term average annual precipitation from 24-hour rainfalls of 0.5 inch or greater may be obtained from a map as shown in Figure 3, an example derived from precipitation records.

$$P = \frac{P_f}{P_p}$$

$= \frac{\text{Value selected from Figure 3 (example only)}}{\text{Average annual inches of 24-hour rainfalls of 0.5 inch or greater for period of advance of the existing gully.}}$

(For example, if recent years were droughty, the P_p would be considerably less than the P_f, or long-term average of precipitation.)

$$P^{0.20} = \left(\frac{P_f}{P_p}\right)^{0.20}$$

Values for $P^{0.20}$ may be read directly from Figure 4 (for use in the calculations).

1/ Climatological Data, U.S. Dept. of Commerce, Weather Bureau, Monthly Summaries were used in developing the map illustrated in the Figure 3 example.

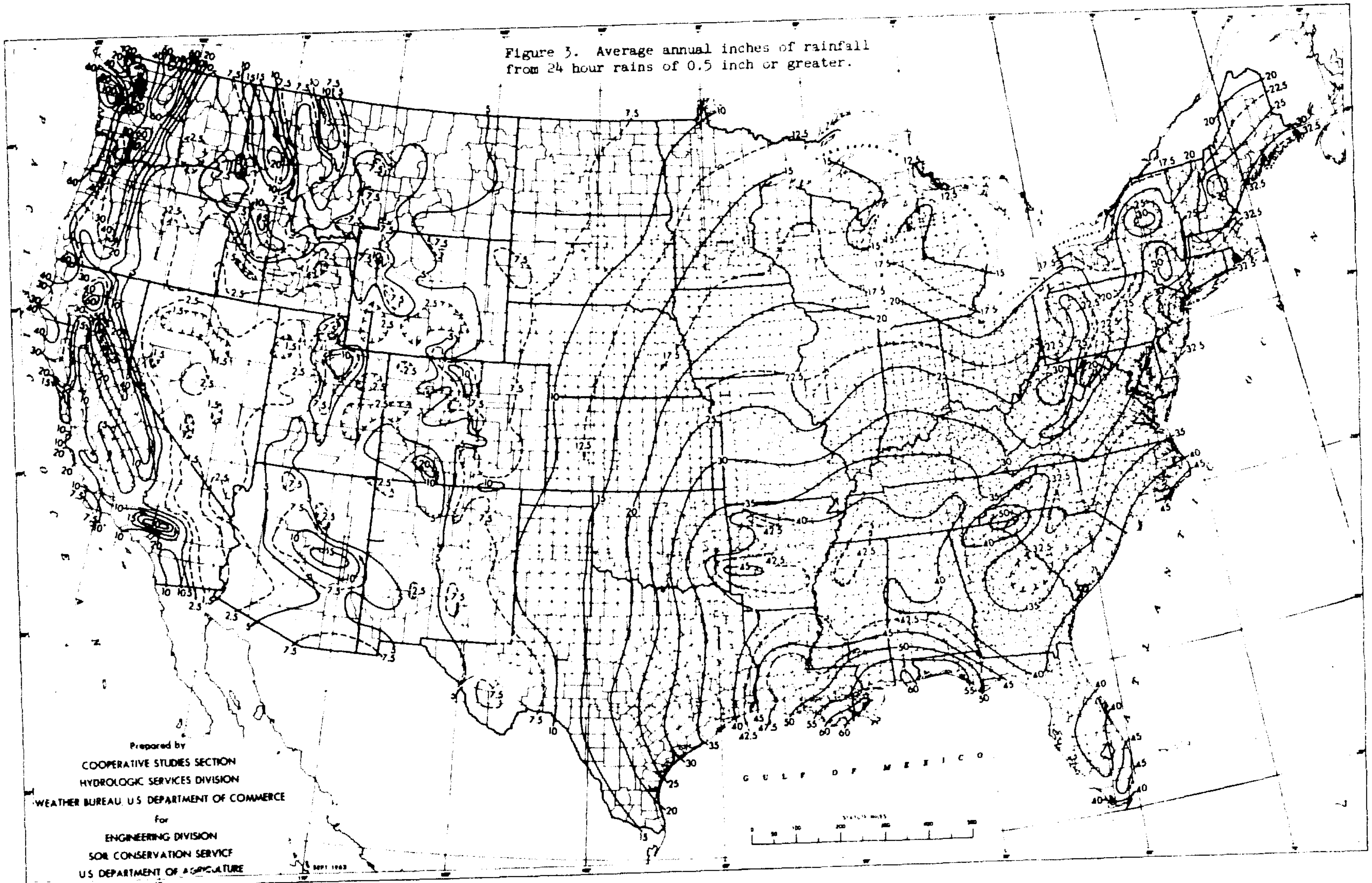

Figure 3. Example of average annual inches of rainfall from 24 hour rains of 0.5 inch (13 mm) or greater in an example for USA showing isohyets, based on rainfall records. (This is the value P_f.)

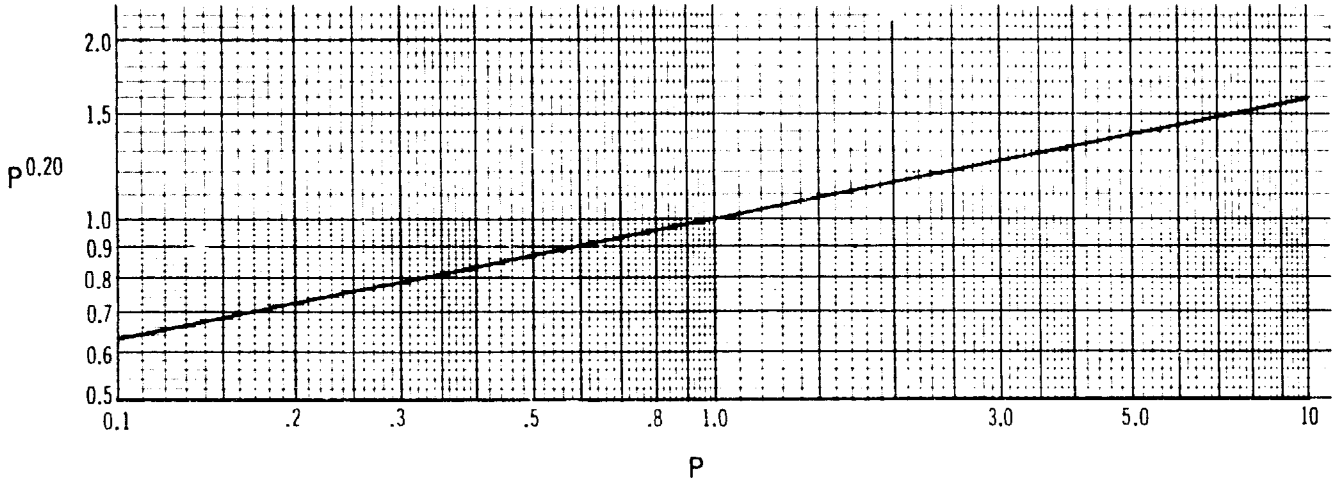

Figure 4. Graph for Obtaining the 0.20 Power of Ratio P

4.4 Adjustment for Type of Material

If the future gully will advance through materials similar to those in which it advanced in the past, there will be no change in the rate of advancement due to change of materials and no adjustment is needed. The value may be greater or less than 1.0 if a significant change in the soil materials exists upstream from the present gully. If the composition of the materials in the upstream reaches has a smaller proportion of clay material, it is generally more erodible and a factor greater than 1 should be used. If the material becomes more cohesive in the upstream reaches, it is generally more resistant to erosion and the adjustment of future advancement would be downward (less than 1). Adjustments are made by multiplying the computed rate of advance and the adjustment factor.

4.5 Adjustment for Ground Water

The rate of gully head advancement may change if the gully head intersects a water table or a gully channel emerges above a water table. Observations indicate that the rate of gully head movement may be accelerated in zones where ground-water seep exists at the foot of the overfall or may slow down when progressing above a water table. No quantitative measurements are known which evaluate the effects of ground-water on the rate of gully head movement. Where no change in ground-water conditions is anticipated, no adjustment should be made. Where a gully head intercepts a water table, or where the water table is expected to rise due to land treatment measures, the rate may require an adjustment upward. Conversely as a gully advances it may rise above the water table and require a downward adjustment in the rate.

Each gully must be evaluated as a separate case in terms of the characteristics of the materials, stratigraphy, and ground-water conditions. Judgment must be used in assigning a realistic value. Adjustments are made, as for the type of material mentioned, by multiplying the computed rate of advance by the ground-water adjustment factor.

5. THE PROCEDURE FOR ESTIMATING FUTURE RATES OF GULLY ADVANCEMENT (EXAMPLES)

The following is a step-by-step procedure demonstrating the method used to determine rates of headward advancement of gullies. A work sheet with appropriate column headings as shown in Figure 5 makes a convenient form for calculating future rates of gully head advance. Figure 1 shows a schematic map of a gully for use with the following step procedure.

STEP 1

a) Determine from aerial photographs, maps, and/or other sources the length of gully eroded in a given period of time.

Example

Using aerial photographs, checked by rough field data, the total length of gully eroded is found to be 1200 feet, Reach A-B, Figure 1. (Note metric conversion table above.)

b) Determine by interviews or other means the age of the gully.

Example

Age of gully = 15 years

c) Compute the past average annual rate of gully elongation.

Example

The average annual rate of past headward advance equals "R"

$$R_p = \frac{\text{total length of gully}}{\text{age of gully}} = \frac{1200}{15} = 80 \text{ ft./yr}$$

d) Enter this in column 8, figure 5. "Rp" is the same for each reach delineated above the existing gully.

STEP 2

a) Using aerial photographs and/or topographic maps, draw a map with the watershed boundary of the area contributing to the gully (Figure 1), comparing with on-the-ground checking.

b) Mark the location of: (1) the earliest position of the active gully (Station A) at a known date as determined in step 1a and the boundary of the area contributing run-off to this head, (2) the present position of the active gully head, B, and the boundary of the area contributing run-off to this head, (3) the selected points where the future cutting head positions may be (these future head positions will logically be located where present or potential tributaries join, where major changes in land use occur, and where probable locations of interception or departure from water tables exist as C,D,E, etc.), (4) the boundaries of areas contributing run-off to each of these points, and (5) the apex of the watershed (see Figure 1).

c) Enter the head positions (Stations), designated A, B, C, etc. in column 2, Figure 5.

Figure 5. Tabular Sheet for Calculation of Rates of Gully Head Advancement

(1) Reach	(2) Station	(3) Reach Length (feet)	(4) D.A. by Station (acres)	(5) Mean D.A. (acres)	(6) A	(7) $A^{0.46}$	(8) R_p (ft/yr)	(9) $P^{0.20}$	(10) [(7)(8)(9)] R_f (ft/yr)	(11) Years to Erode (3)÷(10)	(12) Accum. Years
	A		364								
A-B		1200		352	1.00	1.00	80	1.00	80	15	15
	B		339								
B-C		1400		283	0.80	.90	80	1.00	72	20	20
	C		226								
C-D		1200		182	0.52	.74	80	1.00	59	20	40
	D		137								
D-E		1400		96	0.27	.55	80	1.00	44	32	72
	E		54								
E-F		1300		43	0.12	.38	80	1.00	30	43	115
	F		31								
F-APEX		1500		16	0.05	.25	80	1.00	20	75	190
	APEX										

For 50 year evaluation period, the gully will advance:
1400 ft.*/ + 1200 ft.**/ + (10 yrs. x 44 ft.)±/ = 3040 ft. in 50 years

*/ 1400 ft. in first 20 years

**/ 1200 ft. in second 20 years

±/ 50 years - (20 yrs. + 20 yrs.) = 10 years
10 years at 44 ft/yr = 440 feet

(Note metric conversions, Section 3, above.)

d) The gully head positions or Stations are points that delineate the "reaches" (A–B, B–C, C–D, etc.). Enter reach designations in column 1 as shown in Figure 5.

e) Record the horizontal distance between the head positions as the reach length in column 3, Figure 5.

f) Measure the area contributing run-off to each of the gully head positions and enter these area values in column 4, Figure 5.

Example

Station	Drainage Area (Acres)
A	364
B	339
C	226
D	137
E	54
F	31

g) Determine the mean drainage area for each reach (this is the average between succeeding stations). Enter this figure in column 5, Figure 5.

Example

The mean drainage area for reach C–D is $\frac{226 + 137}{2} = 182$ acres.

h) Determine the A values. These are the ratios of the mean drainage area of of each succeeding reach to the mean drainage area of reach A–B (reach A–B is the present gully or a segment of the present gully with a known average annual head advancement rate). Enter the A values for each reach in column 6, Figure 5.

Example

$$\text{The A value for reach C–D} = \frac{\text{mean drainage area of reach C–D}}{\text{mean drainage area of reach A–B}} =$$

$$\frac{W_f}{W_p} = \frac{182}{352} = 0.52$$

i) Using Figure 1, obtain the values for $(A)^{0.46}$. Enter these in column 7 of Figure 5.

Example

$$A^{0.46} = (0.52)^{0.46} = 0.74$$

Reach	Mean Drainage Area	(A)	$(A)^{0.46}$
A-B	352 (W_p)	1.00	1.00
B-C	283 (W_f)	0.80	.90
C-D	182 (W_f)	0.52	.74
D-E	96 (W_f)	0.27	.55
E-F	43 (W_f)	0.12	.38
F-APEX	16 (W_f)	0.05	.25

STEP 3

Consult availabe climatological (rainfall) data. Select the station nearest to the gully area being evaluated. Tabulate the 24-hour rainfalls of 0.5 inch, or greater, for the period during which the present gully has advanced. Sum these values and divide by the number of years of record. This gives the average annual inches of 24-hour rainfalls of 0.5 inch or greater. Consult the map shown in Figure 3 and select the appropriate value for the expected long-term average annual total 24-hour rainfalls of 0.5 inch or greater. When precipitation records for the period of gully advance equal or exceed 10 years no comparison should be made, (in other words gullies older than 10 years have more likely experienced the "average" rainfall in terms of their life).

Example

a) In this instance, the rainfall record for the period of gully advancement exceeds 10 years. Since some points on the map (Figure 3) are based on only ten years of record, no comparison is made. The ratio P equals 1 in this case. Enter this value in column 9, Figure 5. The same value is used in the evaluation of each successive reach.

b) As an alternate example, assume the period of gully growth had been only five years. Then, from precipitation data available for the general area of the gully it would be found that the summation of rains equal to or exceeding one-half inch in 24 hours for the five years of gully advancement was, for example, 95 inches. Therefore, the average annual amount of rain of one-half inch or more in 24 hours for the five years of record was 95/5 or 19 inches. From Figure 3 the long-term average annual precipitation value by interpolation between lines is 18.0 inches.

The ratio P would be $\frac{P_f}{P_p} = \frac{18}{19}$ or 0.95

From Figure 4 the 0.20 power of 0.95 is found to be .99. This value would be entered in column 9, Figure 5 for future reach.

STEP 4

This now makes available the figures needed to calculate equation (2). On Figure 5, multiply the values on each line in columns 7, 8 and 9 ($A^{0.46} \times R_p \times P^{0.20}$), this product equals Rf, the calculated rate of future gully advancement, in column 10. The number of years required for the gully to pass through each reach is determined by dividing the values in column 3 by those in column 10. Enter these values in column 11. The accumulative years are entered in column 12. From these computations, the distance the gully head will advance in a 50-year evaluation period may be determined.

Example

It will take the gully head 20 years to advance through reach B-C, a distance of 1400 feet; 20 years to erode through reach C-D, a distance of 1200 feet. In the remaining 10 years it will erode at the rate of 44 feet per year into reach D-E, a distance of 440 feet.

20 yrs. + 20 yrs. + 10 yrs. = 50 yrs
1400 ft. + 1200 ft. + (10 x 44 ft.) = 3040 ft.

The preceding procedure does not recognize any physical conditions which would hinder or stop gully advancement other than the limitation of watershed area. Certain physical barriers such as buried rock ledges may alter the advancement rate. Stabilization structures or road culverts will be the termination point of gully advancement evaluation.

6. MOVEMENT OF GULLY HEADS INTO TRIBUTARY DRAINAGEWAYS

In steps 1-4 above it was estimated that the gully head would advance 3040 feet during a 50-year evaluation period. On Figure 4 are shown several tributary drainageways to the main drainage. As the gully head that is advancing up the main drainage passes the junction points with the tributary drainageways, base levels of the tributaries are lowered and gully heads may begin moving up the tributaries. The rate of movement of the gully heads up the tributaries is estimated by the same method as described in steps 1-4. One difference, however, is in the time involved in the growth of the tributary gullies during the 50-year evaluation period.

Example

Tributary I shown to enter the main drainage at station C. It was estimated (line 4, column 11, Figure 5) that the gully head in the main drainage would reach station C in 20 years. Since a gully head will not start to move up tributary I until after the gully head on the main drainage passes station C, the period for evaluating the gully advancement on tributary I will be 50-20 years or 30 years. The evaluation periods for the gully head movement in tributaries II and III will be of successively shorter duration.

Where a large number of tributaries exist, it may not be practical to evaluate each lateral individually. In this case, a few representative laterals should be selected for evaluation. The gully head advancement rates for the duration of the evaluation period may be extended to the remaining laterals.

7. MIGRATION OF KNICKPOINTS

Compute the rate of migration of knickpoints. A "knickpoint" is usually the "head cut" of a later cycle of degradation occuring in an existing gully. Knickpoint development persists in most gully channels until the channel reaches base level. The rate of advancement of knickpoints is an important consideration from the standpoint of sediment produced as it affects the ultimate depth and, therefore, the width of the gully. In general, the same variables that affect the rate of advance of the head also influence the rate of migration of a knickpoint until equilibrium or base level is established. Beyond this state no deepening will occur. Minor widening may continue after base level is reached due to such processes as sheet erosion, animal activity, freeze-thaw and slumping.

The final grade at which a gully channel will stabilize is dependent upon the nature of materials in the channel bed and depth and velocity of flow on the channel bed. With all other conditions being equal, and considering age as an element, the gradient of a gully bed normally (except for highly erodible materials such as fine to medium-grained sand) is inversely proportional to the size of the drainage area. Thus, the smaller the drainage area the larger the gradient. The equilibrium grade or base level must, therefore, be estimated to determine the ultimate termination of knickpoint advance.

8. METHOD OF ESTIMATING GULLY WIDENING

One method of determining the widening that will occur during the next 50 years is to project upstream the widening that has already occured for a distance equal to the computed future headward advance.

Example

In step 4 it was computed that the gully head would advance 3040 feet from its present location during the 50-year evaluation period. Therefore, the widening will advance this distance upstream from its present location.

Many advancing gullies, however, do not maintain uniform top widths and depths. Often advancing secondary knickpoints widen and deepen the gully channel; the base level gradient can usually be determined by spot measurement of older, nearby gullies in the resource area.

Comparison of the top widths and depths of a large number of gullies shows the following relationships:

1. On the average, where the gully advances through cohesive materials, the gully width is about three times the depth.

2. In non-cohesive materials the gully width is about 1.75 the depth.

When a knickpoint migrates up an existing gully channel, the gully channel will widen to adjust to the new requirements for slope stability caused by deepening of the channel. Figure 6 or 7 may be used to estimate the future top width of the gully channel with the new gully depth created by a migrating knickpoint.

Example

A gully channel in cohesive materials that presently is about 15 feet deep and 45 feet wide is being deepened by a migrating knickpoint to a depth of 20 feet. Reference to Figure 6 shows that the gully channel will widen to about 60 feet as a result of the 5 feet of additional depth.

Another method may be used to estimate the amount of gully channel widening that will occur. If there are numerous existing gullies in the same problem area as those to be evaluated, measurements may be made of several of these gullies to establish an average depth-top width ratio. This ratio may be used to estimate the future top-width dimensions of gullies that are undergoing change because of knickpoint migration.

Determine, by the above procedures, the total area in acres of the land estimated to be voided by the gully during the evaluation period. Also determine the rate of land loss in acres per year for the same period.

9. DAMAGE

9.1 Land Damage

Since damage is physically expressed in terms of the area voided by the gully system, the future gullied area as determined in the procedure above represents the land damage area. This area, in terms of acres, is to be provided the economist for evaluating land damage.

9.2 Land Depreciation

The determination of future land depreciation is a joint responsibility of the economist and the geologist or land manager. To assist in this determination, the land manager or geologist will provide a map or a sketch showing the expected extent of gully development at the end of a period - (the actual period should be shown). This includes the main gully and its expected tributaries. Boundaries of expected gully development, including tributaries, are to be shown on maps or drawings with solid lines. The boundaries of all depreciated areas are to be indicated by broken lines. Aerial photographs, soils' maps, land capability maps, and land use maps are ideally suited for this purpose because of the additional information they register. However, base maps and topographic maps are acceptable. Approximate property boundaries added to the map or sketch aid in determining depreciated areas.

The geologist can be particularly helpful in delineating depreciated areas where physical conditions will be altered with resulting depressed yields due to gully development. Thus, if a future gully channel advances to a point where it intercepts and lowers a ground water level to the extent that depressed yields will result, the approxmiate area of influence should be delineated for computing depreciation. For example, it is not unusual for the gullying of mountain meadows to lead to the replacement of grass land cover with less desirable species.

Gully head advancement up a natural draw or waterway which might serve as a present or potential terrace outlet for terraceable land depreciates all of the land which would be served by the terrace outlet.

9.3 Other Damage

Where potential gullies move headward to a road culvert, it is to be assumed that such headward advancement will be halted at this point. In respect to road bridges, however, such advance may continue headward beyond the road resulting in undermining the bridge and necessitating high maintenance or costly replacement.

There are other forms of damage such as potential damage to farm buildings and other structures. In all cases the geologist and economist must work together to anticipate and evaluate potential damage.

10. SEDIMENT PRODUCTION

The sediment produced is computed from the total amount of gully void reduced to an average annual rate. The volume of void can be computed by multiplying the area of land damaged, as computed previously, by the average depth. This should be done by reaches if the gully is not of regular shape. Tributaries should be computed individually. The volume of void then must be converted to equivalent weight in order to express the sediment produced in total tons or tons per unit area (or for questions of reservoir siltation volumes may be of interest).

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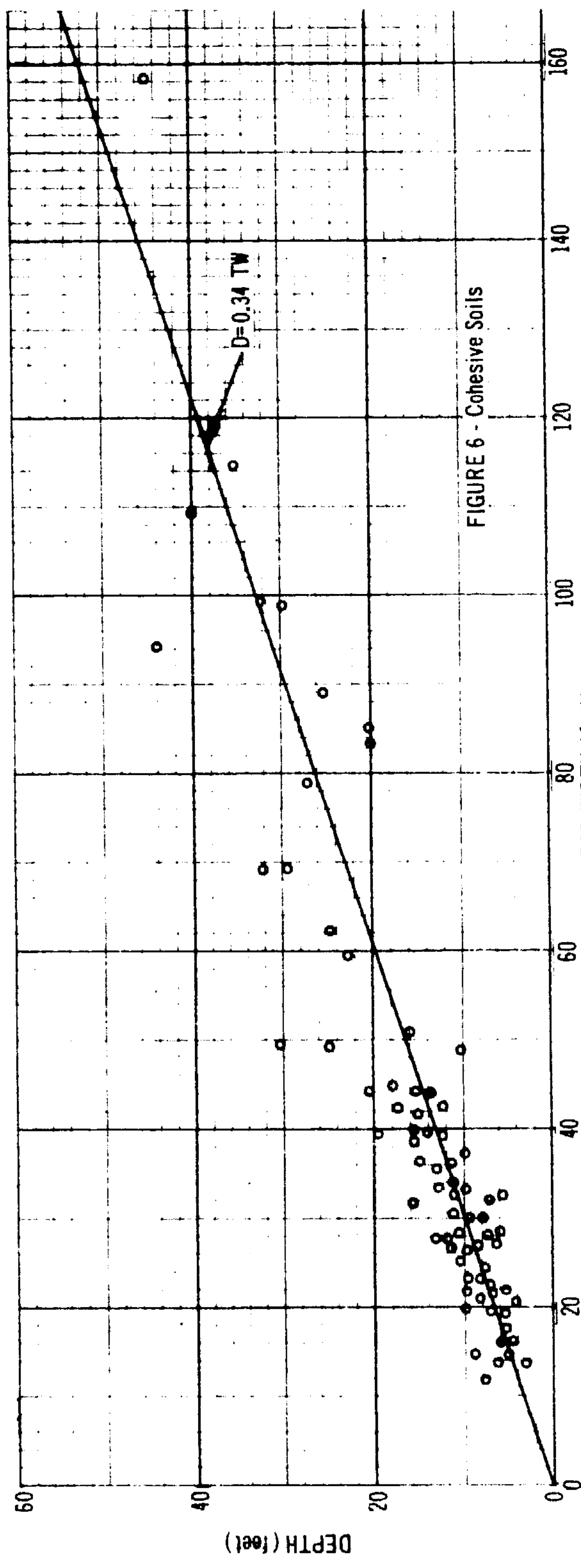

FIGURE 6 - Cohesive Soils

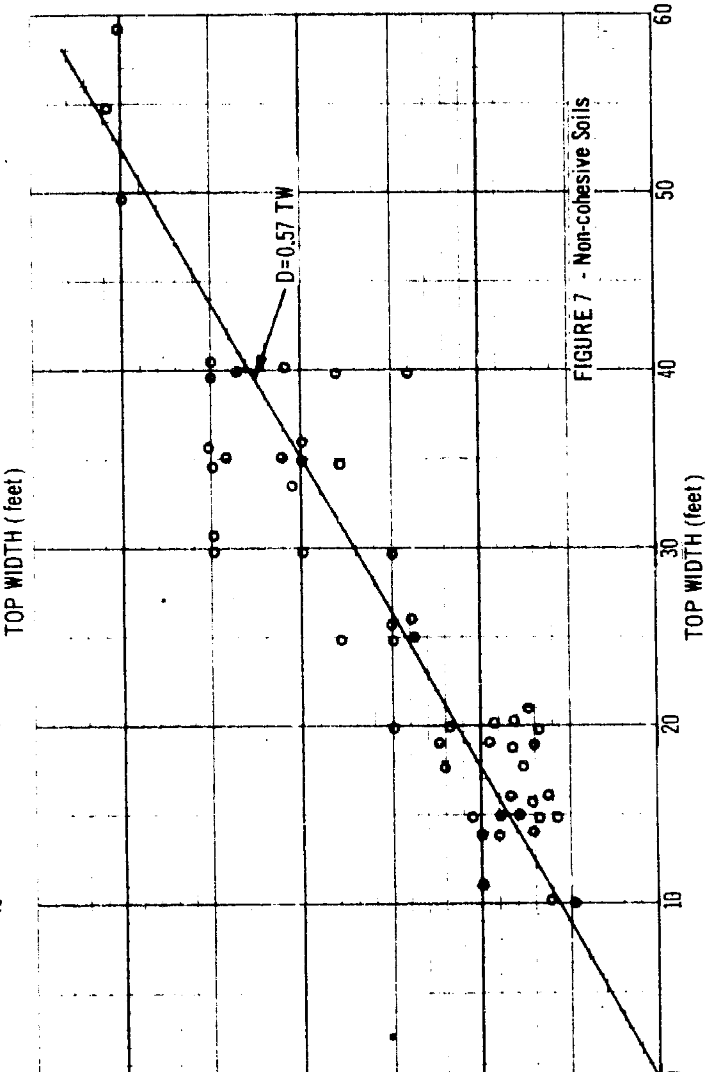

FIGURE 7 - Non-cohesive Soils

Where land damage and depreciation are not being evaluated, other methods are to be used to determine sediment yield for sediment storage requirements or evaluating depositional damages. The use of this procedure is not required for sediment yield computations because in most instances, particularly in larger watersheds, the amount of sediment derived from gully erosion is usually only a minor part of the total which includes that derived from sheet erosion. The minor differences which would result in the total does not warrant the additional work involved in this procedure for refinement of results.

Where sediment yields derived from gully erosion is computed for evaluating downstream sediment damages, judgment must be used in determining the delivery ratio of sediment in respect to the location of downstream sediment damage areas.

Figure 8. Severe erosion by gullies following poor land management practices (Note man in photograph at top). A common problem.

X.

USE OF RUNOFF PLOTS TO EVALUATE SOIL LOSS

by

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1. DESCRIPTION OF PLOT CONSTRUCTION

Simple runoff plots can be used to sample surface runoff and soil loss directly. They are inexpensive and easily constructed. Thus, a sufficient number can be installed to obtain a representative sampling of the major characteristics of a study area, e.g. slope, soil type, plant cover, cultural practice, etc. The plots are rectangular with the long axis oriented up-slope. They consist of a border, an element to concentrate runoff at the lower end of the plot and a collector to contain the runoff and sediment produced on the plot (Figure 1).

Plot borders may be constructed of sheet metal, wooden planks, concrete or earth berms. However, the smaller the plot the greater the necessity for sharp, accurately aligned borders so as to minimize edge effects. Berms should be used only on very large plots of 0.5 ha or more. The borders of our plots were constructed of 0.5-1.0 mm thick, 25 cm wide aluminium strips; 20 cm of the strip was carefully buried in the soil with 5 cm extending above the soil surface. Although a continuous strip around the entire length of the plot would have been preferable, overlapping lengths of 2 to 3 m performed well. The dimension of runoff plots can vary depending upon the area of uniform slope available and the treatment or type of plant cover. We found 20.0 by 2.5 m satisfactory.[2]

2. COLLECTORS

The element for concentrating and directing runoff into the collector is constructed of sheet metal and is much like a flattened funnel with a hinged cover to facilitate cleaning (Figure 2). The sheet metal floor of the element is installed 5 cm below the soil surface, with a strip of sheet metal on the upslope side flush with the soil surface to provide a sharp boundary at the plot end.

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2/ Ed. Note: The standard U.S. Soil Conservation Service erosion plot, used to calculate the parameters of the universal soil loss equation, measures 72.6 by 6.0 ft (about 24.0 by 1.8 m). See also the paper by Arnoldus in this series.

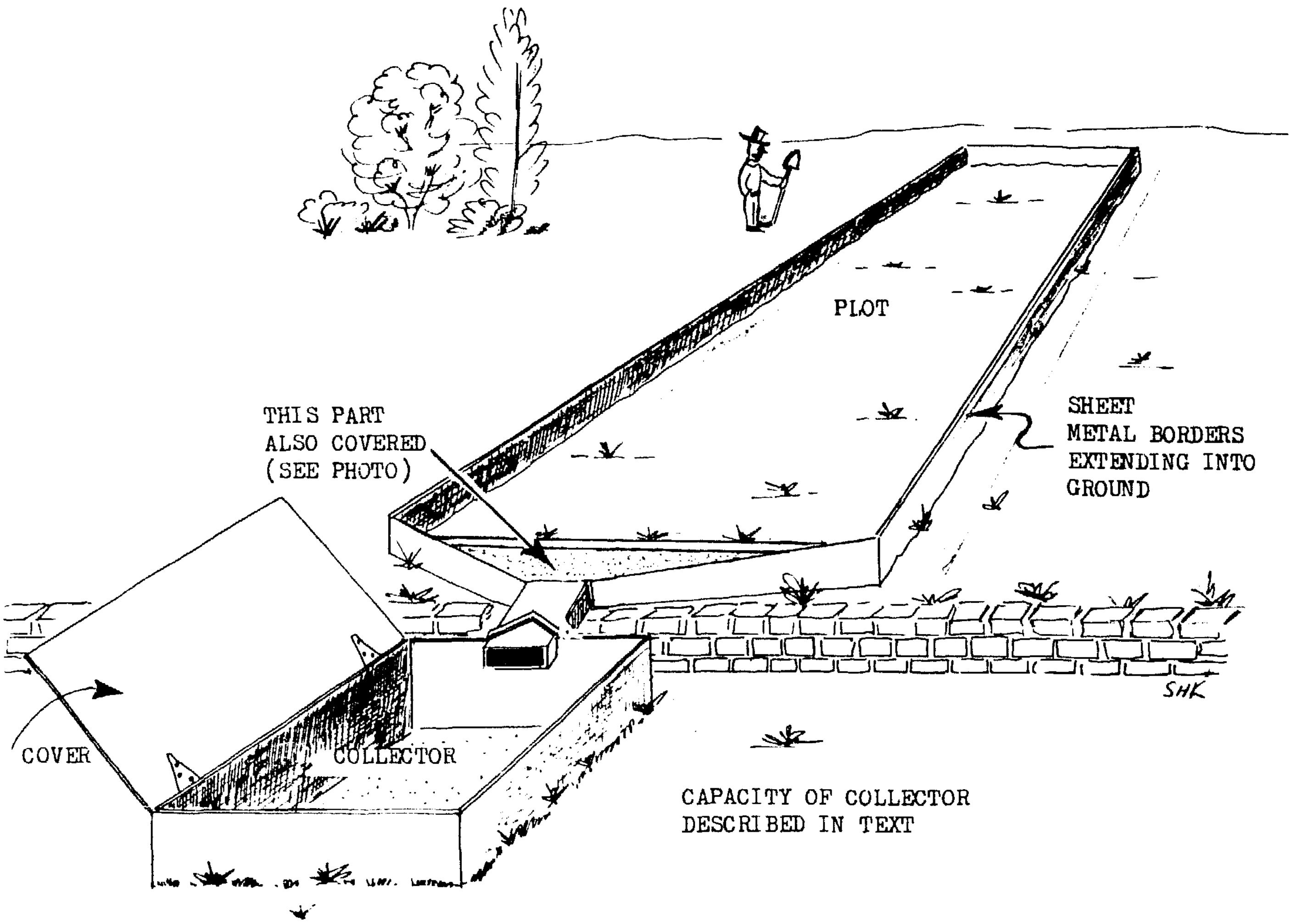


Figure 1 - Sketch of a simple runoff plot

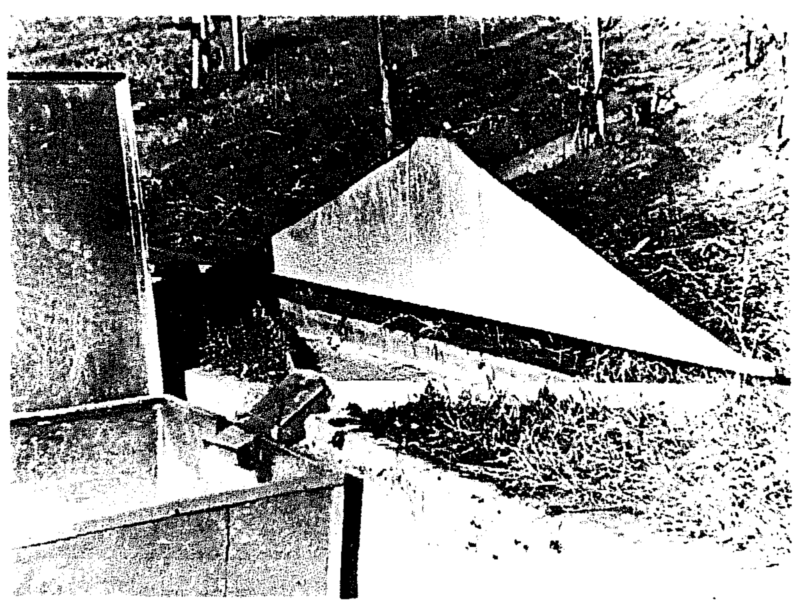


Figure 2 - Details of element for concentrating runoff, showing collector

The collector should be constructed of sheet metal and should have a capacity adequate to contain all the runoff and sediment produced by the maximum probable storm (Figure 3). The required capacity of the collector may be calculated by:

$$W = F \times h \times f$$

where: W = volume of the collector (litres)

F = area of the runoff plot (m^2)

h = maximum storm size at 1% probability level (mm)

f = coefficient of runoff (%)

As a safety factor, particularly for impermeable soils, f may be assumed equal to 100%. If the plot produces more runoff than can be collected reasonably, a split sampler may be used. This consists of a slotted device that diverts 0.10 of the overflow from the primary collector into a secondary collector. An example of such a device appears in Figure 4.

3. SAMPLING PROCEDURE

A portion of the sediment collected will remain in suspension and a portion will be deposited in the bottom of the collector (Figure 3). If the quantity of material deposited is not great and of fine texture, the water in the collector can be agitated with a paddle to disperse the material. Three samples of one-litre size are taken, filtered and the residue dried at 105°C and weighed. The laboratory technique is described by Rapp in this series of papers. The total amount of suspended sediment in the collector is determined by multiplying the average dry weight of the samples by the volume of water in the collector.

If there is a large quantity of deposited sediment or if it is coarse textured, the collector must be drained and the material weighed. If it is not possible to over-dry the entire quantity, then it must be sampled. Three samples are taken and weighed before and after oven drying at 105°C to determine the water content, which is used to convert the total wet weight of the deposited sediment to dry weight.

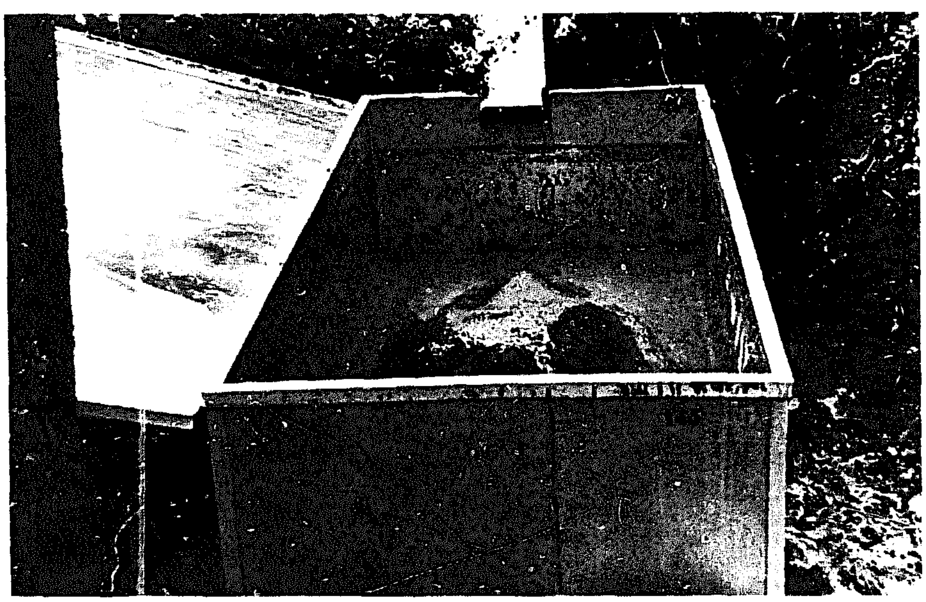


Figure 3 - Collector partly drained with deposited sediment

4. EXAMPLE

The calculations for an assumed runoff event on a plot with an area of 50 m^2 and a collector volume of 2 m^3 is as follows:

Plot calculations

1. Depth of runoff in collector: 0.5 m
2. Value of runoff: $2.0 \times 0.5 = 1.0$ m^3
3. Average weight of sediment in one litre = 16 g
4. Total dry weight of suspended sediment: 1 000 lit. x 10 g = 10 000 g = 10.0 kg
5. Total wet weight of deposited sediment: 30 kg
6. Average wet weight of sample of deposited sediment: 50 g
7. Average dry weight of sample of deposited sediment: 35 g
8. Fraction of water in deposited sediment: $(50 - 35)/35 = 0.428$
9. Total dry weight of deposited sediment: $30/1.428 = 21$ kg
10. Weight of total soil loss: 10 kg + 21 kg = 31 kg

Conversions

1. Runoff per hectare: 1 000 lit./50 m^2 = 20 lit./m^2 = 200 000 lit./ha = 200 m^3/ha
2. Weight of soil loss per hectare: 31 kg/50.0 m^2 = 0.62 kg/m^2 = 6 200 kg/ha
3. Volume of soil loss per hectare (assuming bulk density or 2 t/m^3) : 6 200/2 000 = 3.1 m^3/ha

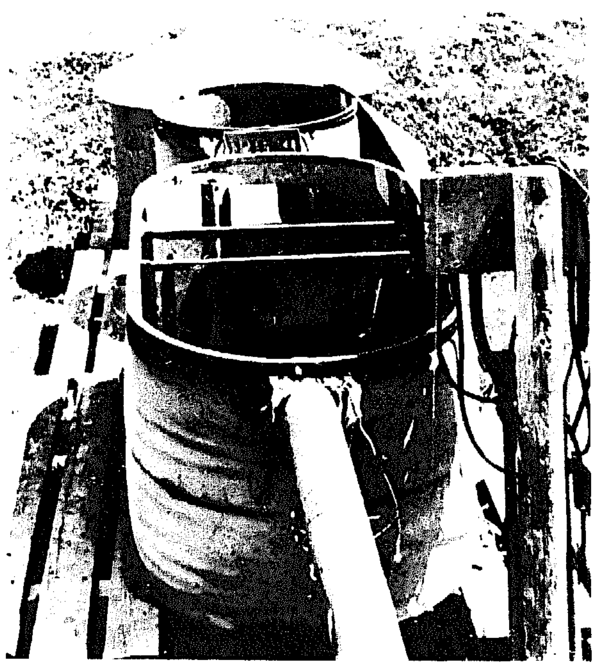


Figure 4 - Slotted device between primary and secondary collectors

XI.

PROTECTION OF CULTIVATED SLOPES

Terracing Steep Slopes in Humid Regions

by

T.C. Sheng
Watershed Management Officer, FAO 1/

1. INTRODUCTION

Cultivation on steep slopes in humid countries without protection measures often causes serious watershed problems. The results are not only deterioration of the productivity of the land "on site" by water erosion but also aggravation of the silting and flood damage "off site", i.e., the downstream area. In the developing countries, the problems are further compounded by the fact that these cultivators of steep slopes are mostly poor small farmers. The dilemma is always there: whereas resettlement and changing of land use may not be feasible or desirable from the socio-economic standpoint, the country's land and water resources are under constant threat by such cultivation.

By applying terracing and protected waterways, these steep slopes could be cultivated safely and profitably. Crop production can be increased, erosion minimized, farming environment improved and hence the dilemma alleviated.

There are essentially four types of bench terraces, i.e., level, outward sloped, conservation bench and reverse sloped (see Figure 1). For this chapter, discussion will be concentrated on the last type, viz., reverse sloped type, which is built sloped inversely towards the hill and is particularly suited for steep humid countries in safe draining of excess runoff.

For the level irrigation type bench terrace or rice paddy, the design and construction are less complicated than the reverse sloped ones. There should be no problem in handling it after understanding the reverse type. The outward sloped terraces and conservation benches are for arid or semi-arid regions. These are dealt with by other authors.

2. KIND OF TERRACES: THEIR SPECIFICATIONS AND APPLICATIONS

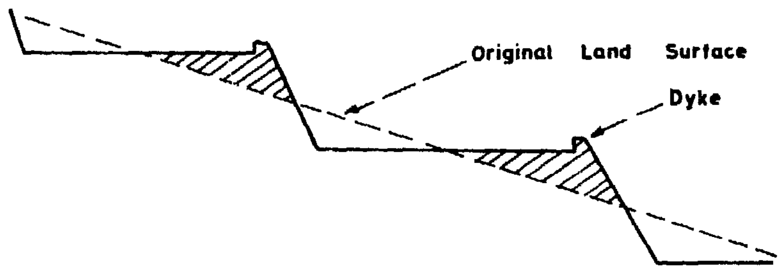
Six kinds of terraces, all reverse sloped, are discussed: (1) bench terraces, (2) hillside ditches, (3) individual basins, (4) orchard terraces, (5) mini-convertible terraces and (6) hexagons. The cross-sectional views of these terraces are shown in Figure 2. With these six kinds of land treatment, slopes between 7° to 30° can be safely cultivated.

1/ This paper stems from the author's work, until recently, in Jamaica. (As of 1975 he is working for FAO in El Salvador).

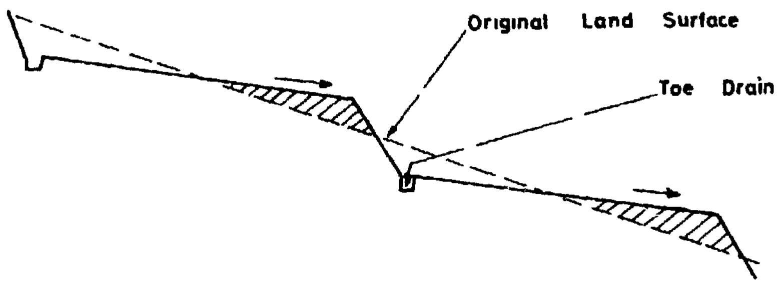
Figure 1

TYPES OF BENCH TERRACES

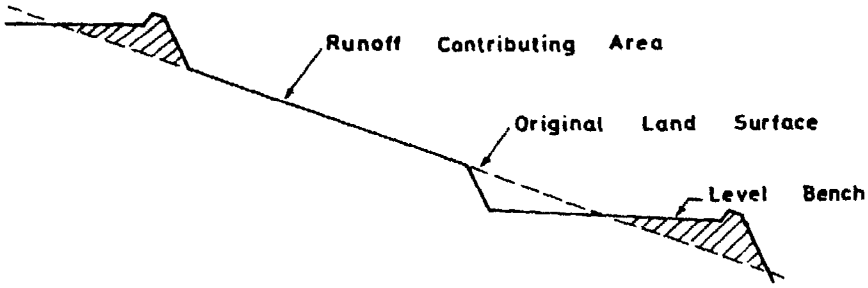
1. LEVEL BENCH TERRACES



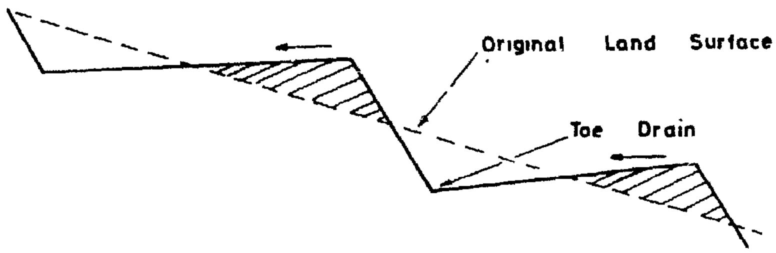
2. OUTWARD SLOPED TERRACES



3. CONSERVATION BENCH TERRACES



4. REVERSE SLOPED TERRACES



2.1 General Description

2.1.1 Bench terraces

They are essentially a series of level or nearly level strips running across the slope supported by steep risers. The risers are either built by earth protected with grass or by rock walls, if rocks are available. Bench terraces can be built and cultivated by manual labour, animal draughting tools or by machines. The detailed cross-sectional view, terminology and computations of this type of bench terrace are shown in Figure 3.

2.1.2 Hillside ditches

The hillside ditch is a discontinuous kind of narrow, reverse-sloped terrace built across the land in order to break long slopes into a number of short slopes so that the runoff will be safely intercepted and drained before causing erosion. The cross-section of this kind of narrow bench is more convenient for maintenance than the conventional type of ditch. They can also be used simultaneously as roads. The distance between two ditches is determined by the degree or percent of the corresponding slope. The cultivable strip between two ditches should be supplemented with agronomic conservation measures.

2.1.3 Individual basins

Individual basins are small round benches for planting individual plants. They are particularly useful for establishing semi-permanent or permanent crops on slopes for controlling erosion, conserving fertilizers and moisture if mulched, and keeping weeds away. They can be applied to dissected lands with varying depth of soils. They should normally be supplemented by hillside ditches or orchard terraces.

2.1.4 Orchard terraces

Fundamentally, orchard terraces are narrow bench terraces built on very steep slopes, from 25° to 30°, and their spaces are determined by the planting distance of the fruit or food trees. Because of steepness, the spaces between should be kept under permanent grass. The trees can be planted either on the terraces or on the individual basins in the grass strips.

2.1.5 "Mini-convertible" terraces

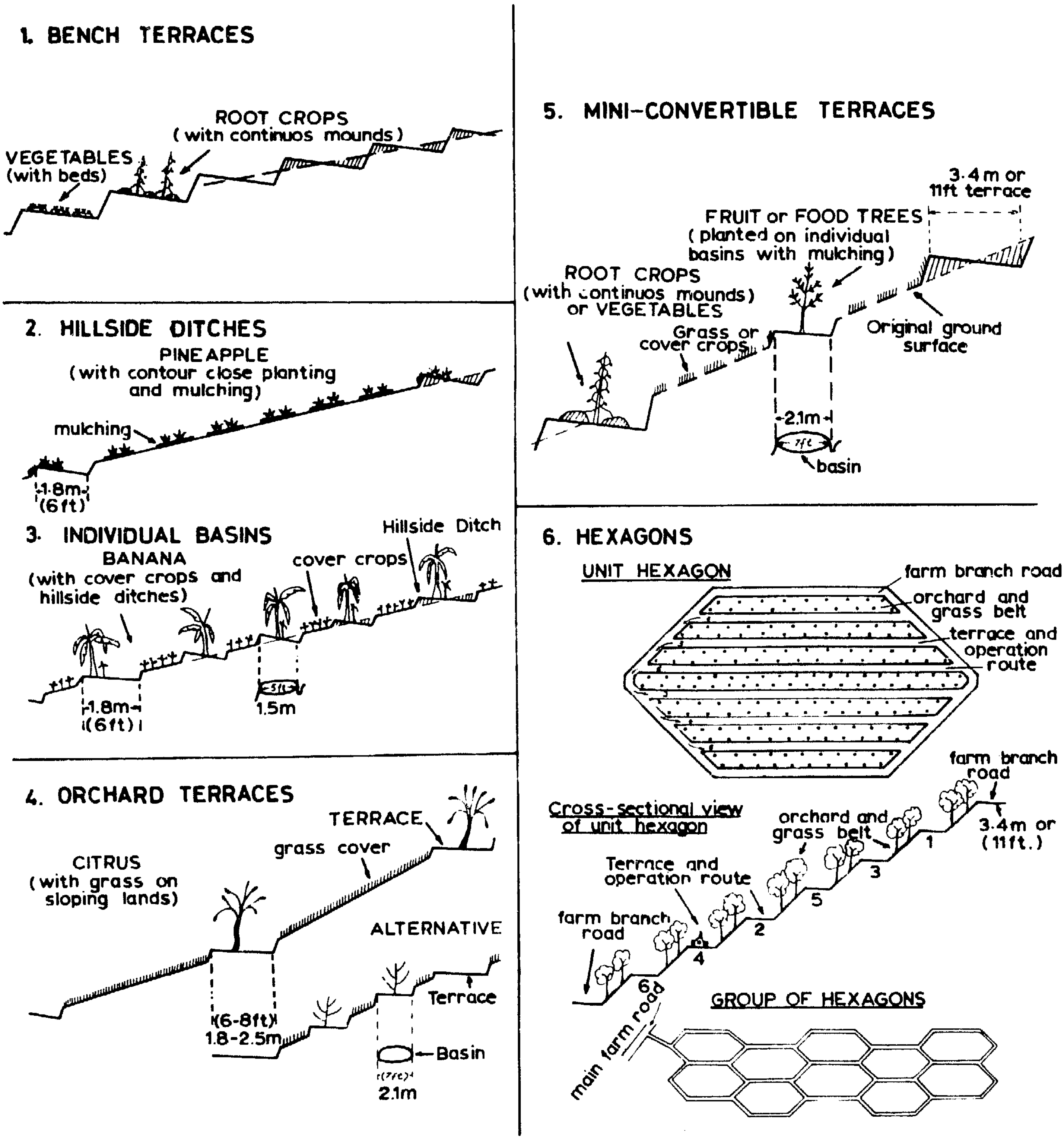
"Mini-convertible" terraces are terraces of medium width built according to the distances used for hillside ditches. Field crops are planted on the terraces whereas fruit or food trees are planted in between. Should the future use of sloping lands be more intensive than today, the spaces between terraces could then be converted also into terraces. If the reserse is true due to labour shortage, then all the terraces could be planted to orchards.

2.1.6 Hexagons

A unit hexagon is a special arrangement of farm road on a slope that envelops a piece of land which can be easily accessible to four-wheel tractors. The enveloped road or branch road goes around the slope to connect with each operation route or terrace which is entered by an obtuse angle. A group of hexagons forms a honeycomb with no land wasted. This land treatment is primarily for mechanization of orchards on a large block of uniform terrain. It can also be applied on steep slopes (such as 20°) for a small farm (quarter hectare). In the latter case, the operation routes could be cultivated to produce cash crops until the food or fruit trees in the grass strip grow up.

Figure 2

CROSS SECTIONAL VIEWS OF SIX MAJOR LAND TREATMENTS



2.2 Specifications and Applications

The specifications and applications of the above mentioned six major treatments are summarized in Table 1. Some supplementary notes are given in the following sections:

2.2.1 Width

For bench terraces, the proper width should be determined first by the crop needs, tools to be used, soil depth and slope, as well as farmer's interest and his financial position. Too wide a bench (flat strip) will not only be too costly but also needs a deep cut and results in very high risers which is undesirable. The widths listed for hand made and machine built bench terraces in Table 1 show their approximation ranges. For hillside ditches and orchard terraces, 1.8 m or 6 feet wide is usually sufficient although the latter can be wider when soil is deep and the slope is around 25°. A width of 3.4 m (11 feet) is found as minimum requirement for machine built terraces and for mechanization.

2.2.2 Vertical intervals and spacings

(1) Bench terraces

To find out the vertical interval (VI) is the next important step after determining the width because it not only gives the approximate height of the riser, but also gives the basic data for calculating the cross-section and the volume of soil in a unit area. It is also used as a guide for staking terraces on the ground.

The vertical interval (VI) is actually the elevation difference between two succeeding terraces. It is determined by the slope of the land and the width of the benches, using the following formula:

$$VI = \frac{S \times Wb}{100 - S \times U}$$

Where VI : vertical interval in feet or metres
S : slope in percent (%)
Wb : width of bench in feet or metres
U : slope of riser (ratio or horizontal distance to vertical rise using value 1 for machine built terraces and 0.75 for hand made ones)

(2) Hillside ditches and mini-convertible terraces

This is the same equation as used in the North American countries for broad base terraces:

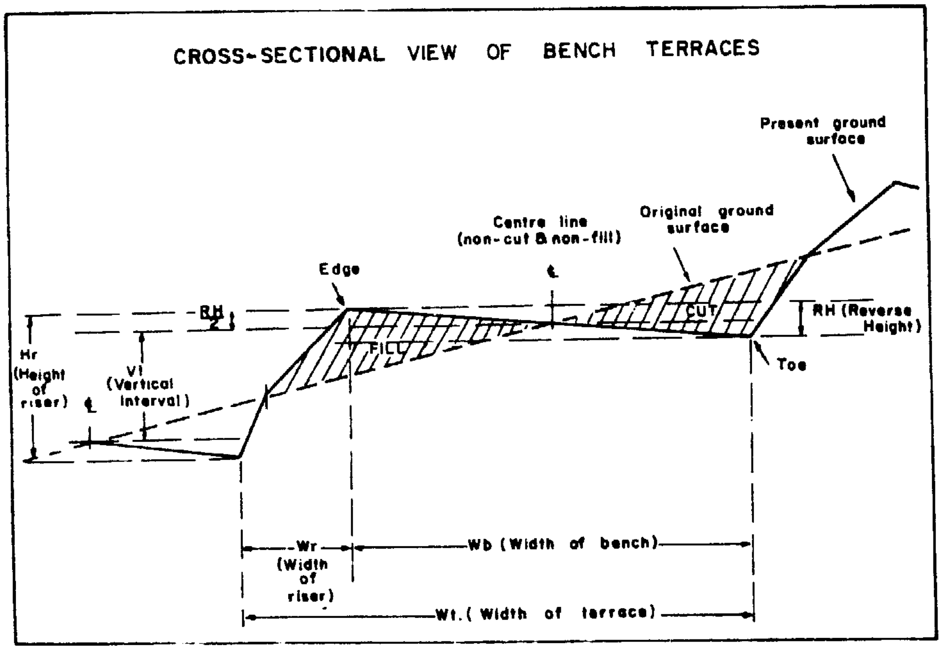
$$VI = aS + b$$

Where VI : vertical interval between two ditches in feet
S : slope in percent (%)
a : constant of geographical location
b : constant for soil erodibility and cover condition during critical periods

The value of "a" and "b" varies from region to region and to the soil and cropping conditions. However, 0.3 is used for "a" in humid conditions whereas 2 is used for "b" where auxiliary conservation treatment is applied to the spaces between. In Jamaica, a table of spacings of hillside ditches on various slopes has been worked out and proved very useful as shown in Table 2. The same table can be used for mini-convertible terraces.

Figure 3

CROSS-SECTIONAL VIEW AND COMPUTATIONS OF BENCH TERRACES



1. Vertical Interval (VI) : $VI = \frac{S \times Wb}{100 - S \times U}$
   (S : Slope in %.
   U : 1 or 0.75)
2. Reverse Height (RH) : $RH = Wb \times 0.05$
3. Height of Riser (Hr) : $Hr = VI + RH$ (Depth of cut $= \frac{Hr}{2}$)
4. Width of Riser (Wr) : $Wr = Hr \times U$
5. Width of Terrace (Wt) : $Wt = Wr + Wb$
6. Linear Length (L) : $L = \frac{43,560}{Wt}$ (per acre)

   $L = \frac{10,000}{Wt}$ (per ha.)
7. Net Area of Benches (A) : $A = L \times Wb$
8. Per cent of Benches (Pb) : $Pb\ (\%) = \frac{A}{43,560} \times 100$ (per acre)

   $Pb\ (\%) = \frac{A}{10,000} \times 100$ (per ha.)
9. Cross Section of Terrace (C) : $C = \frac{Wb \times Hr}{8}$
10. Volume to be cut and filled (V) : $V = L \times C$

In other humid countries where the metric system is used, a similar equation is employed as follows:

$$VI = \frac{S + 4}{10} \quad \text{or} \quad VI = \frac{S + 6}{10}$$

Where VI : vertical interval in metres
S : slope in percent

2.2.3 Length

The length of a terrace is limited by the size and shape of the field, the degree of dissection and the permeability and erodibility of the soil. Longer terraces will increase operation efficiency in future cultivation, especially for mechanization; they also reduce cost of construction. However, too great a length in one direction may cause accelerated runoff and erosion. Based on current experience, a maximum of 100 m (330 feet) in one direction is recommended for humid countries.

2.2.4 Grade

It is very important to control the grades of a terrace. In areas of light rainfall and permeable soils, the horizontal grade can be lower than 0.5 percent, whereas in an area of intense rain and heavy soil, one percent is preferable to get rid of the excess runoff. A reverse grade of 5 percent is also required for the bench terraces in order to keep the runoff at the cut area or the toe drain, rather than on the loose fill area which is susceptible to sliding. For narrower terraces, a 10 percent reverse grade is needed.

2.2.5 Riser and riser slope

The height of the riser is dependent on the width of the terrace. Too high a riser is always a risk for protection and maintenance. A height of 1.8 m to 2 m (6 ft to 6.5 ft) after settling is found to be a practical limit. Table 3 shows the heights of risers in relation to some land slopes and widths of benches.

The slope of a riser depends on the texture of the soil, the tools and materials to be used for building the terrace. For average conditions, the riser slope is 1:1 for machine built terraces (including those built by Fresno Scraper, as explained in 4.2) and 0.75:1 for hand made ones, provided they are compacted well enough and eventually protected by a dense grass cover or rock wall.

2.2.6 Minimum soil depth

The minimum soil depth for the bench terraces can be obtained by dividing the height of the riser by two. For the other discontinuous type of terraces, the depth of cutting is equal to the riser height after settling. All these can be calculated using the equations in Figure 3. Table 3 has also shown minimum soil depths required for some widths of benches on different slopes.

2.2.7 Slope limit

Hand made terraces could be applied to a slope range of 7^{o} to 25^{o} (12% to 47%) while the machine built ones from 7^{o} to 20^{o} (12% to 36%). For tree crops, 1.8 m (6 ft) discontinuous type of orchard terraces can be employed up to 30^{o} slope if the soil is deep enough. Thirty degrees (30^{o}) is a practical limit for all kinds of terraces. Otherwise, the riser will be too high and wide and the bench will be too narrow.

It is generally not recommended to use bench terracing on slopes gentler than 7° (12%) for two reasons: ((i) broad based terraces and other simple conservation treatments can be easily adopted up to a 7° slope, and (ii) slopes of 0° - 7° do not usually present obstacles to mechanized farming.

2.2.8 Net area

The net area, or the area in flat benches after terracing, is very important in the context of land use. This can be calculated by the equation listed in Figure 3. It is interesting to note that for a given land slope and riser slope, the net area of the bench terraces will be the same regardless of the bench widths. For instance, on a 13° slope, a hectare or an acre will produce 80% of flat benches cut by hand regardless of whether the bench width is 3 m or 5 m. The steeper the slope, the less net area there will be. On 25° slope, the net area of the continuous type of bench terraces is only 63.5% whereas on 7° slope it is 87.8%.

2.2.9 Specification tables and volumes

A specification table can be computed step by step according to the equations listed under Figure 3 for different widths of bench terraces and different slopes for planning and field uses. The volumes of cut and fill can finally be obtained. The same procedure can also be used for other kinds of terraces except hexagon enveloping roads. Two sample pages of Tables 4A and 4B, one for machine built bench terraces and one for hand made hillside ditches, are given for reference.

3. PLANNING, SURVEYING AND STAKING

3.1 Planning

The planning and layout of terraces should include field examinations of topography, slope, soil depth, texture, erosion, the presence of rocks, present vegetation and land use, and future crop plans, etc. If a conservation farm plan or land capability map is available, it will be most helpful. After carefully examining the above mentioned factors, decisions should be made on the proper kind of terrace, its width and the tools to be used. The vertical interval, the height of riser and the volume to be cut and filled, etc., can be obtained from the specification tables.

Before starting to stake out the terrace, decisions should be made on the site and type of waterway system and road network (see 5.1 and 5.2). Windbreaks, if necessary, should also be located. All of these should be integrated into terracing work. A sketch map for all the decisions about each particular field should be kept for future reference.

3.2 Survey and Staking

There are two ways of surveying and staking out the terraces depending on the tools to be used for cutting the terraces and the kinds of terraces. For both methods, staking should start from the first terrace on the top of the field. After staking out, corrections should be made if the graded contour lines have sharp bends or very uneven widths between them.

3.2.1 Centre line method

This is to survey and stake out the centre lines of the terraces according to the vertical interval. After completing the staking of all centre lines, a line of stake is added in the middle of every two centre lines (cut and fill being equal) by eye judgement to indicate that it is the bottom line of the upper terrace and also the top line of the succeeding lower terrace. In the case of the discontinuous type of terraces such as hillside ditches and orchard terraces, after centre lines are staked out for the distance along the slope, a top line and a bottom line should be set parallel to the centre line at an appropriate distance to indicate the width of the ditch or terrace.

This method is particularly good for all hand made terraces. The centre line should be retained and marked as a guide for the non-cut and non-fill line during the entire period of construction. The area above this line is the cutting area while the area below is the filling area (Figure 3). This method also enables the surveyor to start staking from the proposed waterway by 1% graded contours to ensure the future runoff will come to a desirable spot as outlet.

3.2.2 Two line method

This method does not stake out centre lines. Instead, it is to survey and stake both the upper line and bottom line of a terrace with proper distances to form the planned width of the terrace. A specification table should be consulted to find out the width of the terrace (Wt) which is determined by the width of the bench (Wb) planned on the particular slope.

Before staking, an up-and-down guideline should first be set on a representative slope of the proposed area. Then stakes are set along this line by the terrace width (Wt), or the width of road and grass strip in the case of hexagons. After this is done, graded contour lines can be staked out from each of the guide stakes.

This method is suited to a uniform slope of a large block of land where machines will be employed for cutting terraces.

4. CONSTRUCTION OF TERRACES

Regardless of what kind of tools are to be employed for terracing, the cut and fill should be gradually done and kept equal so that no extra soil needs to be disposed of or taken from another place.

4.1 Construction by Manual Labour

Generally speaking, a man can cut and fill 3.8 to 4 m^3 (or 5 cubic yards) of dirt during eight hours of work. This may vary with the width of the terrace, type of soil and the presence of tree roots or rocks. If the following rules are observed, the work efficiency and quality can be ensured:

(1) Build the terrace when the land is not too dry or too wet.

(2) Start building the terrace from the top of a hill and proceed downslope. In case of heavy rain it will not be washed away. When the top soil treatment is practised, it is necessary to build from the bottom up. Temporary protection measures should then be practised.

(3) The initial cut should be made right below the top stakes. Fill work should be started against the bottom stakes. By doing so, it will eventually reach a desirable grade without over-cutting. Sometimes, rocks can be placed along the bottom lines, or turn the sods along the bottom stake lines before fill.

(4) After every 15 cm (6 inches) of fill, the soil should be compacted firmly by a beater. When the fill is too thick, it can hardly be compacted. Terraces going across existing depression areas should be built particularly strong.

(5) The edge of a terrace should be built a little higher than planned because of settling. The rate of settling may be as high as 10% of the depth of fill.

Figure 4

Operation of Fresno Scraper.
Soils are dumped out and the
Scraper rides on its runners.

(6) Both the reverse and horizontal grades should be checked by level during construction. Corrections should be readily made wherever necessary.

(7) Shape the slope of the riser to 0.75:1.

(8) Waterway shaping should be commenced only after the terraces are cut. Be sure all the terrace outlets are higher than the waterway bottom.

(9) A team of three men for narrower terraces and four for wider terraces will be a good unit for efficient terracing work.

4.2 Construction by Animal Draughting Tools

Ploughs and Fresno Scrapers (see Figure 4) pulled by oxen, horses or buffaloes are employed in many countries in building terraces. The Fresno scrapers, however, cannot be used to build terraces less than 3 m (10 ft) wide. Neither are Fresnos suitable in soils with many large, head-sized rocks. The following are some general rules to be observed:

(1) Do not use Fresnos when the soils are wet and sticky.

(2) If the cut area of the terrace is very hard or with many grasses, it should first be ploughed to allow the Fresno to move the soil.

(3) Start the operation of the Fresno by raising the handle so that the rear of the floor of the scraper is 10 cm (4 in) higher than the cutting edge. This angle will make the scraper cut into the soil easily.

(4) After the bucket is loaded, release the handle and let the scraper slide flat on its bottom to the area of fill for dumping.

(5) Start loading the scraper always at the high point of the cutting area and as soon as it is filled, turn the animal at once and dump the soil parallel along the lower line of the stakes.

(6) Never load the Fresno so heavily that the animal cannot pull it.

(7) In dumping the scraper, raise the handle to a vertical position so that the scraper rides on the runners and the dirt slides forward out of the bucket.

(8) Better efficiency can be obtained if the cutting and filling operations are done by turning the animal continuously without stopping.

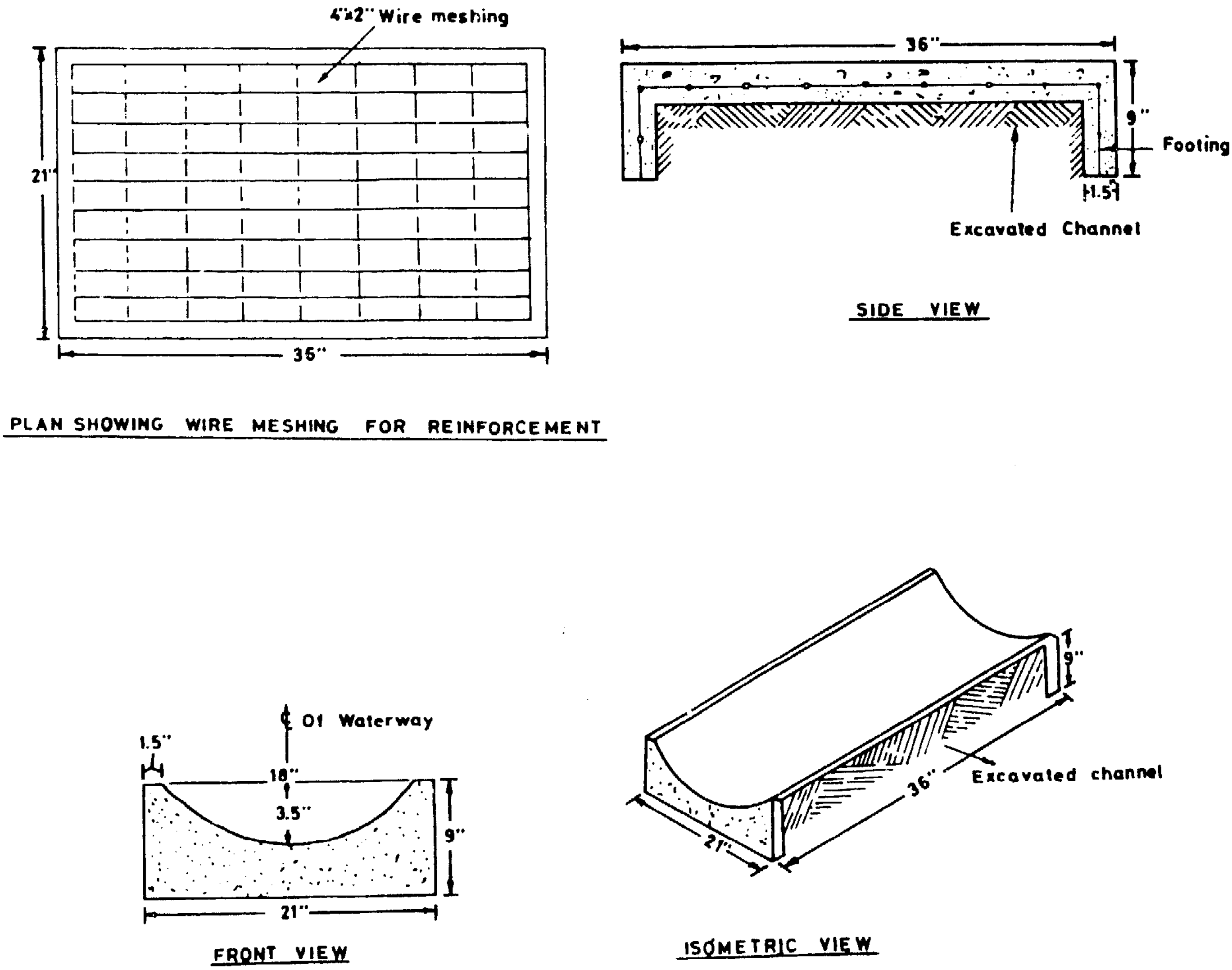
4.3 Construction by Machine

A medium sized machine such as the Caterpillar D-6 bulldozer with angled blade can be employed for cutting wider terraces below 15^{o} slope. A smaller one may be used for cutting narrow terraces on even 20^{o} slopes. So far as efficiency and economy are concerned, the D-6 can do a far better job if the slope is not too steep. The average production per hour for a fairly efficient D-6 bulldozer is as follows:

Width of bench (Wb)		Production per hour	
m	ft	m^3	cubic yds
3.4	11	45.0	58.8
4.6	15	43.5	56.9
5.8	19	42.0	54.9
7.0	23	40.7	53.3
8.2	27	39.7	51.9

Figure 5

PREFABRICATED CONCRETE STRUCTURES



For instance, to cut 0.40 ha (an acre) of 4.6 m (15 ft) wide terraces on a 13° slope, the total volume to be excavated and filled is 596 m^3 or 785 cu.yds (see Table 4A). It would take the D-6 bulldozer 13.7 hours for rough cutting and 2.5 hours for final grading and smoothing. The following are some of the rules to be observed:

(1) Start cutting parallel to and about 50 cm (1.5 ft) from the top line of the stakes and push the dirt down slope and dump it just above the bottom line. The best efficiency will be maintained when the bulldozer travels down slope about three times its length or approximately 12 m to 13.5 m (40 to 45 feet) for dumping.

(2) When it cuts parallel along the top line, attention should be paid to the full load of the bulldozer blade. As soon as the blade is full, not earlier and not much later, the bulldozer should be headed down to the dumping area.

(3) After dumping about 30 cm (1 ft) thick along the bottom line, the dirt should be compacted by the bulldozer. Whenever the bulldozer needs to travel from one end of the terrace to another, it should always run on the edge of the bench for compacting.

(4) Use the angled blade each time for cutting about 40 to 50 cm (16" - 20"). Continue cut and fill until the desirable grades, reversely and horizontally, are attained. Or, mark the elevations of fill at the lower line of stakes with coloured ribbons as check points.

(5) Do not cut or fill at the proposed waterway site, and do not overcut at tne toe drain.

(6) Close supervision is necessary. A dumpy level should be used for checking the grades during construction. Final grading or smoothing should be done as soon as the level checking is made.

(7) Shape the riser slope to 1:1.

4.4 Topsoil Treatment

Bench terraces usually expose the infertile subsoil which could result in lower production unless some prevention or improvement measures are to be taken. One of these methods is topsoil treatment. When fertile topsoil exists, topsoil treatment is always worth undertaking. There are two ways of doing it:

(1) The terraces are to be built from down slope up. After the bottom terrace is roughly cut, the topsoil from the slope above is then pushed down to the bench and spread on it. The next to the bottom terrace, in the same fashion, gets its topsoil from above. This proceeds uphill until the top one is built without topsoil. For a medium sized bulldozer it needs about 8 extra hours to treat one gross acre, or 20 hours per hectare.

(2) The second method is to push the topsoil away to the ends before cutting the terrace and pushing it back when cutting is completed. For hand made terraces, the topsoil can be piled along the centre line or at certain intervals, provided that the bench is wide enough.

5. WATERWAYS AND ROAD REQUIREMENTS

5.1 Waterways

The waterway is an integral part of terracing in the humid regions. In most cases, a natural depression without shaping and protection is not safe to accommodate extra runoff concentrated by terracing. On average, a hectare needs 100 m (330 ft) of waterway. For larger blocks of land, the same waterway could serve up to two hectares. On acre basis, 150 to 200 ft waterway may be needed.

5.1.1 Waterway planning

The site and kind of waterway(s) for a special field depend on the slope, velocity and amount of runoff and the tools to be used for cultivation. It is always desirable to find a gentle depression area for the site of waterway plus shaping and revegetation. When the velocity of runoff exceeds 1.8 m (6 ft) per second, engineering structure are usually needed for additional protection. A grassed waterway alone is seldom safe to be applied on steep slopes, i.e. more than 11° or 20% slope. In the steep hill region, waterway structures cannot be avoided.

The waterway is usually situated at one end of the field. Sometimes, however, two waterways instead of one are needed, one each at both ends of the terraces to handle large quantities of runoff and when the terraces are longer than 100 m (330 ft). Sometimes, a waterway can be installed in the middle of the terrace, leaving two ends for access roads. A stepped waterway (see 5.1.2) could be built in the middle if 4-wheel cultivation is required. Also, the same waterway can be used as a pathway up and down the terraces. On gentle slopes, a waterway can be combined with road ditches for tractor crossing.

The size of waterway is determined by the peak flows of the area; its estimation is not covered in this particular paper. However, waterways wider than 3 m (10 ft) are not desirable on small farms because too much land is taken out of production.

5.1.2 Types of waterways and structures

There are many types of waterways depending on material available, shape of the channel, purposes and structure needs. A waterway can also have many different sections according to the protection needs. The following are brief descriptions of some major types of waterway. Their uses and approximate limits are shown in Table 5 and Figure 8.

(1) Grassed Waterway: A parabolic shaped channel planted with low and rhizome type grass. The channel should be shaped as uniform cross-section and consistent in gradient as possible. It is the most inexpensive type of waterway on gentle slopes and its maintenance is easy.

(2) Grassed Waterway with Drop Structures: On moderately steep slopes or in a discontinuous type of channel, small drop structures and check dams can be used in conjunction with grass to take care of the steep sections. The structure should not be taller than 2 m (6 ft) and the gradient between the apron of the upper structure and the weir of the structure immediately below should not be over 3% to ensure their stability.

(3) Ballasted Waterway: Also on moderately steep slopes where large quantities of head-size stones are available, ballasting the parabolic channel with stones keyed in the ground can provide a good protection. On steeper slopes or for large quantity runoff, wire mesh should be used.

(4) Prefabricated Concrete Waterway: On very steep slopes and where it rains so frequently that normal construction is hampered, these prefabricated structures, parabolic or V-notch type, can be readily used to protect the

centre part of a waterway and leave two sides protected by grass. They can also be used in these channels where there are constant small flows due to seepage or ground water.

(5) Stepped Waterway: A series of drop structures with basins are used to protect the steep risers of the terraces whereas on flat benches, parabolic grassed waterways of 3% are employed to connect the drop structures. The grassed portion on benches can be easily crossed by a tractor and the structures on steep risers can be used for collecting the silt and as pathways. It is usually built in the middle of terraced fields.

(6) Waterway and Road Ditch Complex: To combine road ditch and waterway as one channel on gentle slope is not only economic but also convenient for 4-wheel mechanization. In a case like this, the road should be built reverse-sloped allowing road water drains to the channel and also the terraces should be sloped toward the same channel. The channel should be shaped parabolically and protected with ballasting stones for tractor crossing.

(7) Footpath and Chute Complex: On very steep slopes where mechanization is not applicable, a rectangular or trapezoid type of concrete or masonry chute can be built with steps in the middle for both draining runoff and for use as a pathway. It is particularly welcomed by small farmers.

5.1.3 <u>Waterway installation</u>

(1) Shaping: All types of waterways should be shaped as uniformly as possible in cross-section and gradient. Sharp turns and sudden falls should be avoided unless where a water collecting basin is planned or drop structure is to be built. Structures should be installed on solid cut soils or solid rocks wherever possible. Stakes, strings or bamboo arches to mark the shaping area and depths are in many cases needed. It is also important to shape the waterway lower than the terrace outlets to ensure water flowing in.

(2) Grass Planting: An ideal grass for lining the waterway is one that is available locally and is the rhizome type or sod-forming type. Seeding is cheaper than sodding but it should be done with shallow ditching and mulching at the beginning of the rainy season. Strip-sodding can provide quick protection. Sometimes pegs are used to stabilize the sods. Hydro-seeding techniques which are explained in details elsewhere in this Manual, could also be employed.

(3) Construction of Structures: For design and construction of drop structures, chutes and check dams, other sections of the Manual or a regular civil engineering handbook should be consulted. A diagram of a prefabricated concrete structure for a parabolic waterway used in Jamaica is shown in Figure 5, for reference. One bag of cement with 1:2:4 ratio could produce 3 structures. With a wooden frame, any unskilled farm worker can make the structure.

The following are some important principles regarding the structure construction:

(a) The water must go over the structures and not go around them. This is perhaps the most common cause of structure failure. For drop structures, side walls must be high enough to direct the flow to the weir of the structure and cut-off walls behind, beside and below the structure to prevent water from seeping through are needed. For any type of chute, cut-off walls are always necessary.

(b) Structures must be built on cut and solid soil and the foundations should be deep and strong enough. Steel bars or wire mesh are needed for chutes and for taller drop structures built with cement blocks.

(c) The apron or stilling basin of the drop or chute should be built strong and big enough to dissipate the energy of the falling water and prevent undermining.

(d) Enough good quality mortar should be used to assure that the structure will be watertight and not permit water to flow through causing leakages.

(e) After the structure is built, tramp earth solidly behind or around it to prevent cracking.

(f) Provide sodding at the junction of the earth and the structure to avoid water tunnelling.

5.2 Roads

Roads are also essential to terracing programmes. Although the construction of roads is treated elsewhere in this Manual, the following sections are important to road design and layouts with terracing systems.

5.2.1 For mechanization

Road access to and from terraced area is required for 4-wheel mechanization. On gentler slopes, the roads could be built up-and-down hills. On steeper slopes, they should be built diagonally across the field. The maximum grade for this kind of tractor road is 7° to 8° (12% to 14%). Because bench terraces can be used as roads, there is no need of roads transversing the slope. Generally speaking, 200 m (660 ft) of road per hectare should be ample for even rugged and steep terrains. The appropriate width is 3.4 m or 11 ft.

There are four types of road system which can be used to cope with the different field conditions and mechanization requirements. They are as follows:

(1) Two road system: Two up-and-down roads to connect both ends of the terraces at approximately right angles to the terraces. They are ideal for mechanization on gentle slopes (below 10° or 18%). On large blocks of land, each road could serve two sides.

(2) One road system plus U-turn: On moderately steep slopes or where there is no room for system number (1), this type could be employed. A road is built to connect one side of terraces whereas at the other side, a U-type short road is connecting every two terraces for the tractor to turn around.

(3) One road system: If the benches (flat strips) are wide enough for tractor turning, one road connecting one end of each terrace should be sufficient. Or, the road could go through the terrace field diagonally in the case of steeper slopes and round hills.

(4) Hexagon system: As explained previously, this system is particularly suited to big farms and full mechanization of orchard crops.

5.2.2 For manual or animal cultivation

The road requirements for manual or animal cultivation are less rigid. A width of 2m (about 6 ft) should be ample and the road gradient can be up to 15° (26.8%) or more. One hectare needs about 100 m (330 ft) to 150 m (480 ft) of road.

6. PROTECTION AND MAINTENANCE

Protection measures on newly built terraces, waterways and roads and, thereafter, their maintenance are very essential to the success of the overall terracing programme. Field workers and farmers should carefully examine the terraced area during the first two rainy seasons. Any small damage should be immediately repaired before it becomes worse. "A stitch in time saves nine!" Many terracing programmes have failed not because of design or construction, but owing to negligence in protection and maintenance.

6.1 Protection Measures

6.1.1 For terraces

(1) After the risers are properly shaped, grasses should be planted or hydro-seeded on the risers. Local grasses of rhizome type are much more desirable than tall grasses, although the latter may produce forage for cattle. Figure 6 shows the terrace risers are well protected by carpet grass (*Axonopus compressus*). Use stones for protecting risers, if available.

(2) The terrace outlets which are always critical should be well protected either by sod-forming grasses or by small checks (using a piece of rock or brick to form a check).

(3) On that part of the bench where the stepped waterway is crossing, grasses should also be established.

(4) Auxiliary conservation treatments or grasses should be well established between the discontinuous type of terraces.

6.1.2 For waterways

(1) In most cases, grasses are planted to protect the channel or part of the channel. In rainy season, mechanical support is sometimes needed, such as using pegs to anchor sods or mulching for seeding, during initial stage.

(2) Waterways should be protected from other use, such as paths or for transporting materials.

6.1.3 For roads

(1) Unstable road banks should be protected by various methods, i.e., wattling and staking, sodding or hydro-seeding, etc., which are described elsewhere in this publication.

(2) Steep road surfaces should be protected either by grass, marl or stones. In any case, cross drains are needed. The distance between two drains can be decided by the following formula which is a modification of the one used by the U.S. Forest Service and proved to be very successful in Jamaica.

$$I = \frac{800}{S}$$

Where I : Interval along the road surface by foot

S : Slope in percent (%)

(3) Steep road ditches should be protected by ballasting or a combination of grass and small loose rock checks. Further details on road protection are given in the paper by Megahan in this publication.

6.2 Maintenance

A total of 30 man days a year for maintaining one hectare or 12 man days per acre for bench terraces should be ample. For hillside ditches and orchard terraces, etc., it should be much less.

6.2.1 For terraces

(1) For benches:

(a) Keep the toe drains always open and properly graded and do not permit any accumulation of water in any part of the terraces.

(b) Allow all runoff to collect at the toe drains for safe disposal to the protected waterway. Obstacles like continuous mounds or beds should be broken to permit water passing to the toe drains.

(c) Keep grasses and weeds away from the benches.

(d) Maintain proper reverse slopes of the benches or basins and reshape them immediately after crops are reaped. Ploughing should be done carefully so as not to destroy the toe drains and the reverse grade.

(2) For risers:

(a) Do not allow any runoff to flow over the risers.

(b) Keep grasses growing well on the risers. Weeds and vines which threaten the survival of the grasses should be cut back or uprooted. Grasses should be kept reasonably low and fertilized.

(c) Any small break or fall from the riser should be repaired immediately.

(d) Keep cattle away to avoid trampling on risers or eating the grass.

(3) For outlets:

(a) Check the outlets and see whether they are adequately protected.

(b) Any silt in the outlets should be cleaned.

(4) For soil productivity:

(a) Deep ploughing, ripping or sub-soiling is needed on the cut part of the bench terraces to improve the structure of the soils.

(b) Green manuring, composting or sludge application is also needed in the initial period for improving soil fertility.

(c) Maintain soil productivity by proper crop rotation and fertilizing.

6.2.2 For waterways

(1) Keep the water flowing through the waterways, instead of going around or underneath the structure. Any detectable breaks should be repaired immediately.

Figure 6

Terraces on 15° to 20° slope. Note the risers are protected by carpet grass and a stepped waterway is in the middle (Smithfield Demonstration Watershed, Jamaica).

(2) Brush or large weeds should be removed before they weaken the grass. The whole waterway should be kept in dense and low grass cover and as uniform as possible to avoid a turbulent flow.

(3) Structures should be checked at least twice a year, once before the rainy season and the second after the rains. Any minor cracks, tunnels and breaks around or on the structure should be repaired before they are too big or become very serious.

(4) Clean out silt trapped in the stilling basins. The silt can be put back on the terraces.

(5) Keep stones properly fastened at ballasted waterways.

6.2.3 <u>For roads</u>

(1) Maintain a proper profile of the cross drains and clean silt out of the drains after heavy rains.

(2) Prevent use of the roads by heavy trucks when they are too wet or soft.

(3) Culverts and side ditches should always be kept open.

(4) Re-shape road surface if there appears to be track erosion either by wheels or by hooves of animals.

7. COSTS AND BENEFITS

7.1 Costs

7.1.1 Costs of terracing

The cost of terracing per unit area depends on slope, soil, type of terrace, width of bench, presence of rocks or tree stumps and tools to be employed for cutting them. If the width is fixed, the steeper the slope the more expensive the terracing work will be. If the slope is fixed, however, the wider the bench, the more costly it will be, although the percent of bench (flat area) in a unit area is still the same. If volumes to be cut are the same, machine built terraces are generally cheaper than hand made ones. But, the type of road and waterway required for mechanization may affect the total cost a great deal. Discontinuous type of terraces, i.e., hillside ditches, orchard terraces, etc., generally cost much less than bench terraces.

Figures 7A and 7B show the examples of volumes of soil to be cut and filled per hectare and per acre for one kind of terrace: bench terraces. The equation for calculating the volume is shown in Figure 3. In design and construction of terraces, the volume to be cut should be equal to the fill, so that no extra soil is needed to be borrowed from elsewhere or disposed of. In calculating the volume, therefore, only one part, the cut part, needs to be figured out.

Once the volumes are calculated or found from the specifi cation tables (see 2.2.9), the cost of cutting various types of terraces can be readily obtained from the following equation:

$$C = \frac{v}{T} \times R$$

Where C : cost of cutting terraces

v : volume of cut and fill

T : output per man day or per machine hour

R : wage per man day or rate per hour

The output per man day or per machine hour depends on the site, efficiency of work and tools to be used. On the average, a man with hand tools can cut and fill 4 m^3 (about 5 cu. yds) in one day (8 hours); a D-6 bulldozer can build 42 m^3 (55 cu. yds) an hour; and a man with animal draughting tools (plough and Fresno Scraper) can cut and fill 16 m^3 (20 cu. yds). For hand made individual basins, a man day can build about 18 basins of 1.5 m (5 ft) diameter.

A hectare of 4.6 m (15 ft) bench terraces on 15° slope, for instance, may need 425 man days, 47 bulldozer hours or 106 animal days. Only 41 man days are required to complete one hectare of 1.8 m (6 ft) of hillside ditches on the same slope.

7.1.2 Associated costs and annual costs

Costs of waterways and roads vary from one field to another. Generally, terraces for mechanization should cost more on waterway structures and road construction. If one hectare of bench terraces requires 100 m of waterway and 200 m of road (see 5.1 and 5.2), the cost can be estimated from the labour and material needed to build them. Other costs like riser stabilization, soil improvement (optional cost) and terrace maintenance, etc., can also be estimated according to the actual needs.

Table 6 is an example of total and annual costs of bench terracing in Jamaica (Reference 9). Although these are 1971 figures, the wages and machine rates may be quite close to the prevailing rates in most of the developing countries at present. An annual cost per acre from US$ 70 to US$ 80 or per hectare US$ 175 to US$ 200 with or without soil improvement respectively, should be a fair estimation. For discontinuous types of narrow terraces, the annual cost can be much lower, because the cutting and maintenance costs are less.

In many developing countries, small farmers can use their own labour to complete terracing their own farms bit by bit over 4 to 5 years, with technical service and incentives such as subsidies and cement from the Government. It would not overburden the farmer if the terracing cost - which is mostly family labour - can be spread over a number of years.

7.2 Benefits

7.2.1 Increase of farm production

Terraces can be expected to increase farm production by an average of 20 to 30 per-cent. They conserve fertilizers, moisture and topsoils and gradually build up soil fertility. They also facilitate better cultivation and management. In many instances, the production per unit area has more than doubled. For example, the UNDP/FAO Forestry Department and Watershed Management Project at its Smithfield Demonstration area in Jamaica has tripled the production of both Lucea yam and Yellow yam (*Dioscorea* spp.) in the newly terraced areas. The net return per acre of yam, after deducting the annual cost of terraces, is around US$ 750.

Figure 7A

VOLUMES OF SOIL TO BE CUT AND FILLED PER HECTARE FOR BENCH TERRACES

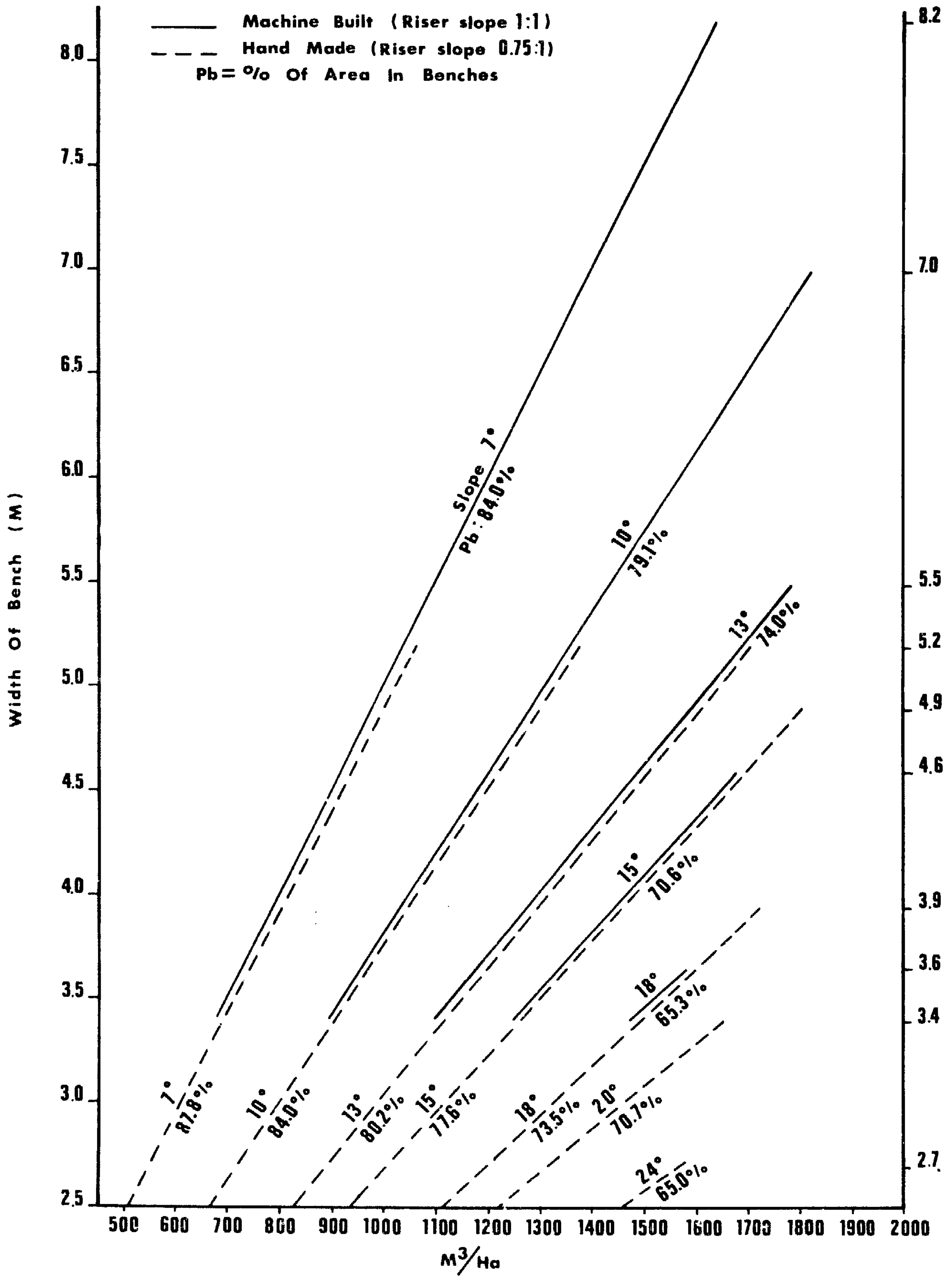
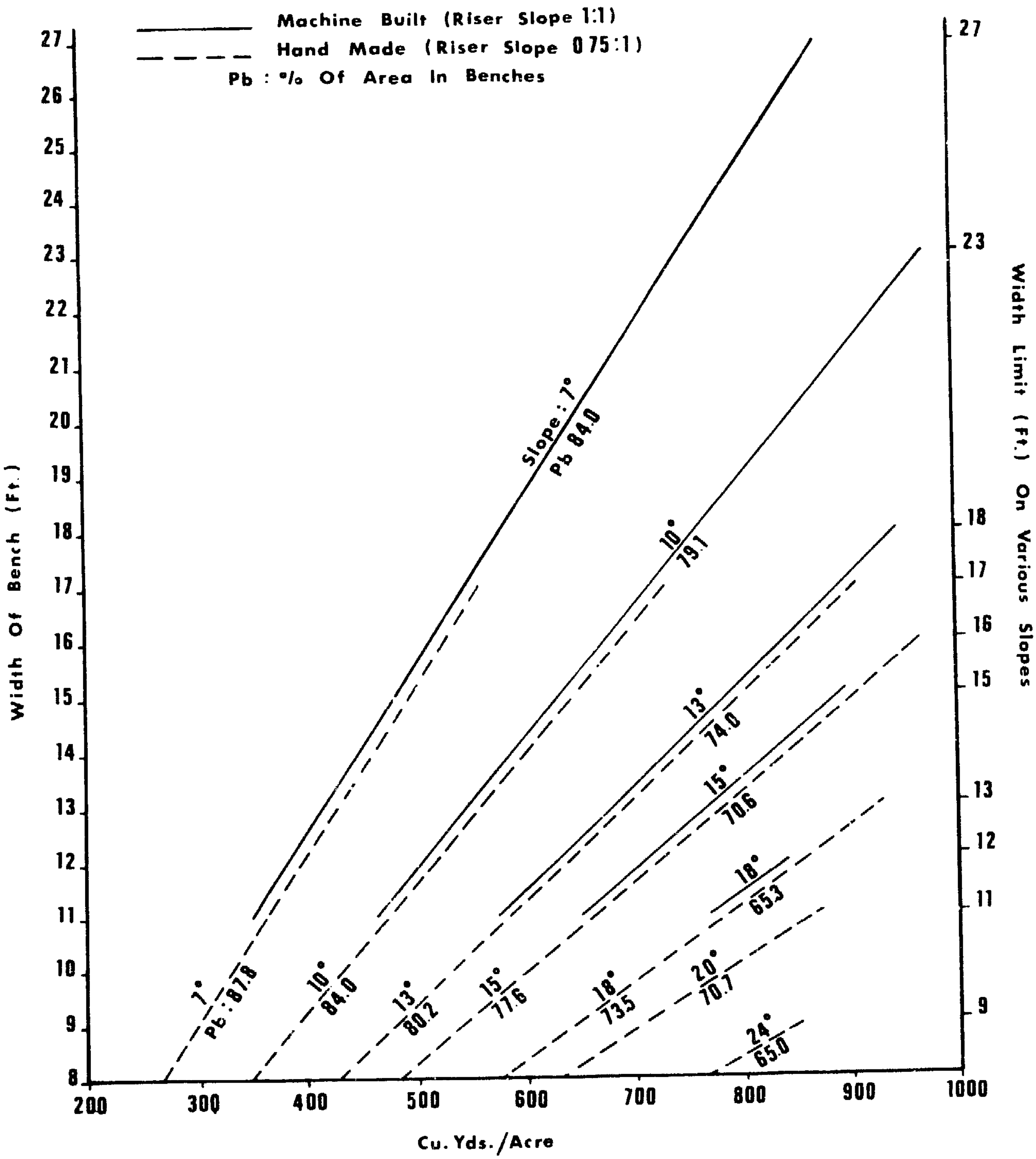


Figure 7B

VOLUMES OF SOIL TO BE CUT AND FILLED PER ACRE FOR BENCH TERRACES



7.2.2 Protection from erosion

Runoff and soil loss plot studies in many humid tropical countries have shown that various types of terracing could cut down a considerable amount of soil loss in comparison with the conventional way of cultivation on the slopes.

For example, the results of a 4-year soil loss experiment on 17° slope in Yellow yams in the northwest of Jamaica where the annual rainfall is 3 250 mm (130 in), showed that an average of dry soil loss per acre per year from the check plot was 54 tons while from the bench terrace plot it was 7 tons. Hillside ditches with continuous mounds or with individual hills yielded 11 tons and 16 tons respectively. In terms of soil depth, the check plot lost 0.43 inches (1.1 cm) a year while the bench terraces lost 0.06 in (0.15 cm).

7.2.3 Other benefits

In addition to the above, terracing programmes have many other benefits as follows:

- Minimize sedimentation and stream pollution
- Reduce runoff and flood damage
- Intensify land use
- Create arable lands and enable free choice of crops
- Stimulate improved farming practices
- Improve drainage and provide better sites for cultivation
- Facilitate mechanization on steep slopes
- Maximize irrigation benefits
- Encourage permanent farming and reduce shifting cultivation and forest fire
- Promote labour intensive programmes and create new job opportunities
- Beautify landscapes and provide better environment

A terracing programme in the long run serves to protect the land and water resources of the country for posterity and for sustained production. It is similar to public health programme or national defence which are all necessary to a nation. A cost-effectiveness analysis of such a programme may be more appropriate than the conventional way of cost and benefit analysis.

When the whole world is troubled by food shortages and environment deterioration, and when many developing countries have idle hands or idle lands in the hilly watersheds, terracing may be one of the best solutions.

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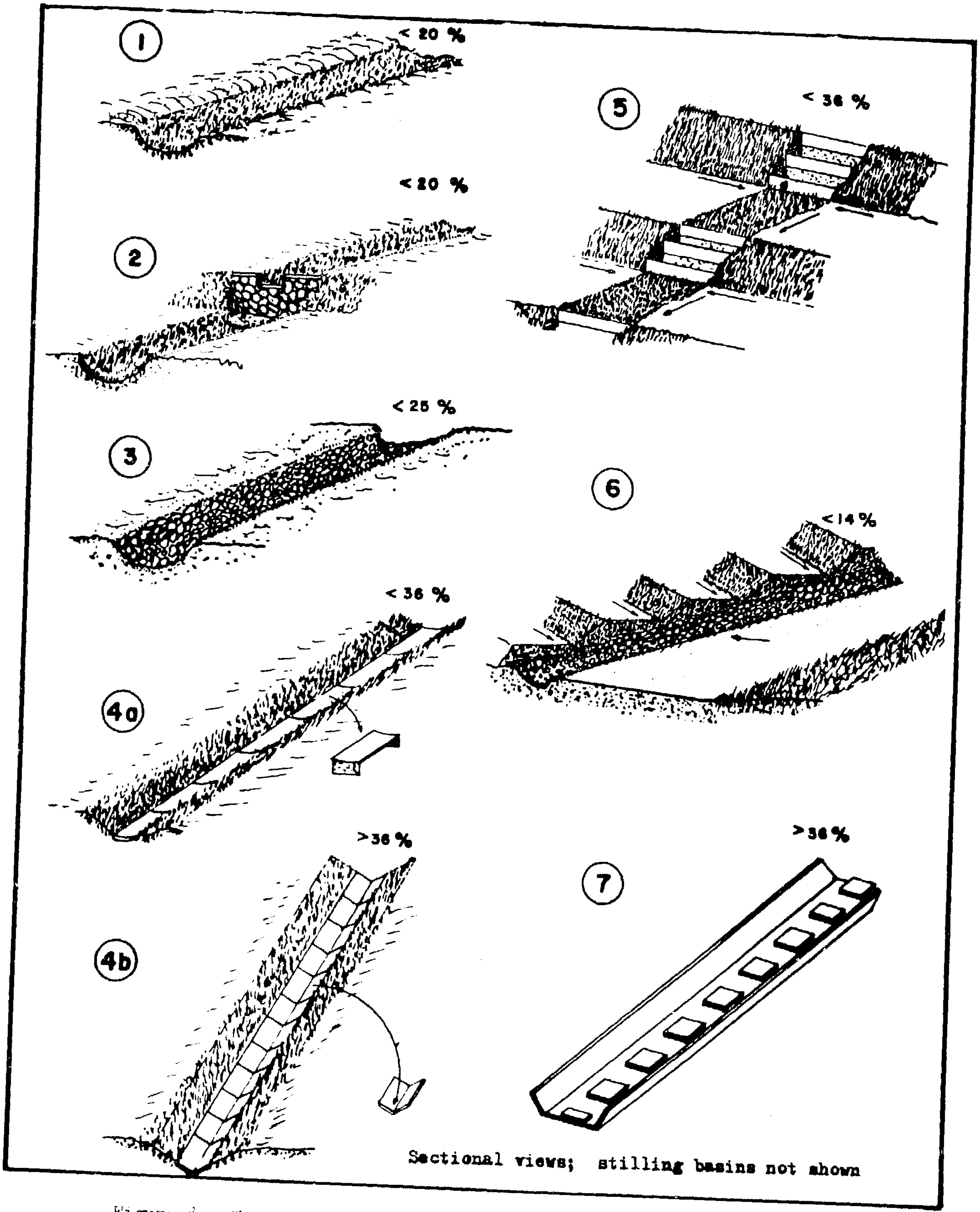

Figure 8. The major types of waterways as described in Table 5

Table 1

SPECIFICATIONS AND APPLICATIONS OF SIX KINDS OF TERRACES

Kind	Specifications: Width of Bench (Flat Part)	Specifications: Length	Specifications: Horizontal Grade	Specifications: Reverse Grade	Specifications: Riser Slope	Applications: Land Slope	Applications: V.I. 1/ or Spacing	Applications: Auxiliary Treatments 2/
1. Bench Terraces								
a. Hand made	2.5-5.2 m (8'-17')	< 100 m (< 330')	1%	5%	0.75 :1	7°-25° (12-47%)	$\frac{S \times Wb}{100 - S \times .75}$	-
b. Machine built	3.4-8.2 m (11'-27')	< 100 m (< 330')	1%	5%	1 :1	7°-20° (12-36%)	$\frac{S \times Wb}{100 - S \times 1}$	-
2. Hillside ditches	1.8 m (6')	< 100 m (< 330')	1%	10%	0.75 :1	< 25° (< 47%)	a S + b	Contour planting Close planting Mulching Cover cropping
3. Individual basins	1.5-2.1 m (5'-7')	1.5-2.1 m (5'-7')	-	10%	0.75 :1	< 25° (< 47%)	Planting distance of crops	Hillside ditches Orchard terraces Mulching Cover cropping Contour planting
4. Orchard terraces	1.8-2.5 m (6'-8')	< 100 m (< 330')	1%	5-10%	0.75 :1	25°-30° (47-58%)	±6m (±20') along slope	Grass cover Individual basins
5. Mini-convertible terraces	3.4 m (11')	< 100 m (< 330')	1%	5%	1 :1	7°-20° (12-36%)	a S + b	Grass cover Individual basins Mulching
6. Hexagons								
a. Terraces and operation routes	3.4 m (11')	< 100 m (< 330')	1%	5%	1 :1	7°-20° (12-36%)	±6m (±20') along slope	Grass cover Individual basins
b. Enveloped or branch road	3.4 m (11')		< 7° (< 12%)	5%	1 :1	7°-20° (12-36%)	-	Grass or marling Cross drains

1/ V.I. is vertical interval between two succeeding terraces that determines space.

2/ To be applied mostly in between the terraces or on basin surfaces.

Table 2

SPACINGS OF HILLSIDE DITCHES ON VARIOUS SLOPES

Slope		Vertical Interval		Spacings or Inclined Distance	
Degree (°)	Per cent (%)	(ft)	(m)	(ft)	(m)
1	1.8	2.54	0.77	145	44.2
2	3.5	3.05	0.93	87	26.5
3	5.2	3.56	1.08	68	20.7
4	7.0	4.10	1.25	58	17.7
5	8.6	4.58	1.40	52	15.8
6	10.5	5.15	1.57	49	14.9
7	12.3	5.69	1.73	46	14.0
8	14.1	6.23	1.90	44	13.4
9	15.8	6.74	2.05	43	13.1
10	17.6	7.28	2.22	41	12.4
11	19.4	7.82	2.38	40	12.2
12	21.3	8.39	2.56	40	12.2
13	23.1	8.93	2.72	39	11.9
14	24.9	9.47	2.88	39	11.9
15	26.8	10.04	3.06	38	11.6
16	28.7	10.61	3.23	38	11.6
17	30.6	11.18	3.41	38	11.6
18	32.5	11.75	3.58	38	11.6
19	34.4	12.32	3.76	38	11.6
20	36.4	12.92	3.94	37	11.3
21	38.4	13.52	4.12	37	11.3
22	40.4	14.12	4.30	37	11.3
23	42.4	14.72	4.49	37	11.3
24	44.5	15.35	4.67	37	11.3
25	46.6	15.98	4.87	37	11.3

Remarks:

1. Spacings may be decreased as much as 25 per cent and increased as much as 10 per cent to allow for soil, climatic, crop and farming needs.

2. From 1 to 6 degrees, the spacings are the same as for the broadbase terraces.

3. These precisely calculated values naturally would be "rounded" as needed for use in the field.

Table 3

RISER HEIGHTS AND MINIMUM SOIL DEPTH REQUIRED 1/
IN RELATION TO SOME LAND SLOPES AND BENCH WIDTHS

Width of Bench (Wb)	Slope	Riser Height	Minimum Soil Depth 1/	Remarks
1. Bench Terraces				
2.5 m (8')	18° (32.5%)	1.17 m (3.84')	59 cm (23in)	Hand made
	25° (46.6%)	1.87m * (6.13')	93 cm (36.6in)	Hand made
3.4 m (11')	11° (19.4%)	0.93 m (3.05')	46 cm (18.3in)	Hand made
	20° (36.4%)	1.84 m * (6.06')	92 cm (36.3in)	Hand made
4.6 m (15')	14° (24.9%)	1.74 m * (5.72')	87 cm (34.3in)	Machine built
5.8 m (19')	12° (21.3%)	1.85 m * (6.09')	92 cm (36.3in)	Machine built
7.0 m (23')	10° (17.6%)	1.84 m * (6.06')	92 cm (36.3in)	Machine built
2. Hillside Ditches				
1.8 m (6')	11° (19.4%)	0.30 m (0.98')	30 cm (11.8in)	Hand made
	18° (32.5%)	0.48 m (1.59')	48 cm (19.1in)	Hand made
	25° (46.6%)	0.75 m (2.45')	75 cm (29.4in)	Hand made
3. Orchard Terraces				
1.8 m (6')	29° (55.4%)	0.97 m (3.14')	97 cm (37.6in)	Hand made
2.5 m (8')	25° (46.6%)	0.93 m (3.06')	93 cm (36.6in)	Hand made
4. Mini-Convertible & Hexagons				
3.4 m (11')	11° (19.4%)	0.49 m (1.60')	49 cm (19.2in)	Machine built
	18° (32.5%)	0.89 m (2.92')	89 cm (35.[illegible]in)	Machine built

* At the limit of the riser height.

1/ Because of calculations and conversions, the precise depths and dimensions shown here will need to be "rounded" as required for field use.

Table 4A

SAMPLE SHEET OF SPECIFICATION TABLES

Specifications of Machine Built Bench Terraces

Reverse Slope 5%
Riser slope 1:1

Width of Bench(ft)	Symbols	Unit (Slope)	13° 23.1%	14° 24.9%	15° 26.8%	16° 28.7%	17° 30.6%	18° 32.5%
13	VI	ft	3.91	4.31	4.76	5.23	5.73	6.26
	RH	ft	0.65	0.65	0.65	0.65	0.65	0.65
	Hr	ft	4.56	4.96	5.41	5.88	6.38	6.91
	Wr	ft	4.56	4.96	5.41	5.88	6.38	6.91
	Wt	ft	17.56	17.96	18.41	18.88	19.38	19.91
	L	ft	2,480.64	2,425.39	2,366.11	2,307.20	2,247.68	2,187.85
	A	ft^2	32,248.32	31,530.07	30,759.43	29,993.60	29,219.84	28,442.05
	Pb	%	74.00	72.40	70.60	68.90	67.10	65.30
	C	ft^2	7.41	8.06	8.79	9.56	10.37	11.23
	V	ft^3	18,381.54	19,548.64	20,798.11	22,056.83	23,308.44	24,569.56
	CY	Yd^3	680.80	724.10	770.40	816.98	863.30	910.00
14	VI	ft	4.21	4.64	5.13	5.64	6.17	6.74
	RH	ft	0.70	0.70	0.70	0.70	0.70	0.70
	Hr	ft	4.91	5.34	5.83	6.34	6.87	7.44
	Wr	ft	4.91	5.34	5.83	6.34	6.87	7.44
	Wt=	ft	18.91	19.34	19.83	20.34	20.87	21.44
	L	ft	2,303.54	2,252.33	2,196.67	2,141.59	2,087.21	2,031.72
	A	ft^2	32,249.56	31,532.62	30,753.38	29,982.26	29,220.94	28,444.08
	Pb	%	74.00	72.40	70.60	68.80	67.10	65.30
	C	ft^2	8.59	9.35	10.20	11.10	12.03	13.02
	V	ft^3	19,787.41	21,059.29	22,406.03	23,771.65	25,088.26	26,452.99
	CY	Yd^3	732.90	780.00	829.90	880.50	929.30	979.80
15	VI	ft	4.51	4.97	5.49	6.04	6.61	7.22
	RH	ft	0.75	0.75	0.75	0.75	0.75	0.75
	Hr	ft	5.26	5.72	6.24	6.79	7.36	7.97
	Wr	ft	5.26	5.72	6.24	6.79	7.36	7.97
	Wt	ft	20.26	20.72	21.24	21.79	22.30	22.97
	L	ft	2,150 05	2,102.32	2,050.85	1,999.08	1,948.12	1,896.39
	A	ft^2	32,250.75	31,534.80	30.762.75	29,986.20	29,221.80	28,445.86
	Pb	%	74.00	72.40	70.60	68.80	67.10	65.30
	C	ft^2	9.86	10.73	11.70	12.73	13.80	14.94
	V	ft^3	21,199.49	22,557.89	23,994.93	25,448.29	26,884.06	28,332.07
	CY	Yd^3	785.20	835.50	888.80	942.60	995.80	1,049.40

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Table 4B

SAMPLE SHEET OF SPECIFICATION TABLES

Specifications of Hillside Ditches   Width: 6ft.
Reverse Slope: 10%
Riser Slope: 0.75:1

Slope	Symbols	Units	Specifications	Slope	Symbols	Units	Specifications
	VIt	ft	1.84		VIt	ft	2.38
	RH	ft	0.60		RH	ft	0.60
	Hr	ft	1.22		Hr	ft	1.49
	Wr	ft	0.91		Wr	ft	1.12
14°	Wt	ft	6.91	17°	Wt	ft	7.12
(24.9%)	L	ft	1,144.00	(30.6%)	L	ft	1,185.60
	A	ft^2	6,864.00		A	ft^2	7,113.60
	Pb	%	15.76		Pb	%	16.33
	C	ft^2	1.83		C	ft^2	2.24
	V	ft^3	2,093.52		V	ft^3	2,655.74
	CY	Yd^3	77.54		CY	Yd^3	98.36
	D	ft	39.00		D	ft	38.00
	VIt	ft	2.01		VIt	ft	2.58
	RH	ft	0.60		RH	ft	0.60
	Hr	ft	1.31		Hr	ft	1.59
	Wr	ft	0.98		Wr	ft	1.19
15°	Wt	ft	6.98	18°	Wt	ft	7.19
(26.8%)	L	ft	1,173.12	(32.5%)	L	ft	1,198.08
	A	ft^2	7,038.72		A	ft^2	7,188.48
	Pb	%	16.16		Pb	%	16.50
	C	ft^2	1.96		C	ft^2	2.39
	V	ft^3	2,299.32		V	ft^3	2,863.41
	CY	Yd^3	85.16		CY	Yd^3	106.05
	D	ft	38.00		D	ft	38.00
	VIt	ft	2.19		VIt	ft	2.78
	RH	ft	0.60		RH	ft	0.60
	Hr	ft	1.39		Hr	ft	1.69
	Wr	ft	1.05		Wr	ft	1.27
16°	Wt	ft	7.05	19°	Wt	ft	7.27
(28.7%)	L	ft	1,185.60	(34.4%)	L	ft	1,198.08
	A	ft^2	7,113.60		A	ft^2	7,188.48
	Pb	%	16.33		Pb	%	16.50
	C	ft^2	2.10		C	ft^2	2.54
	V	ft^3	2,489.76		V	ft^3	3,043.12
	CY	Yd^3	92.21		CY	Yd^3	112.71
	D	ft	38.00		D	ft	38.00

(41)

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Table 5

MAJOR TYPES OF WATERWAYS:
THEIR USES AND LIMITS 1/

Type	Shape	Channel Protection	Velocity Limit	Slope Limit	Uses
1. Grassed Waterway	Parabolic	By grass	1.8 m/sec (6'/sec)	<11° (20%)	For new waterway or uniform sloped depression
2. Grassed waterway with drop structures	Parabolic	By grass and concrete or masonry structures	1.8 m/sec (6'/sec)	Between two structures: 3%, overall slope <11° (20%)	For discontinuous type of channel
3. Ballasted waterway	Parabolic	By stones or by stones and wire mesh	3 m/sec (10'/sec)	<15° (26%)	Where stones are available
4. Prefabricated concrete waterway					A stilling basin is usually needed at the end
a. Parabolic waterway	Parabolic	By concrete structures and grass	-	<20° (36%)	Where rainfalls are frequent and flows are constant
b. V-notch chute	90° V-notch	By concrete structures and grass	-	>20° (36%)	Same as above and on very steep slopes
5. Stepped waterway	Parabolic and rectangular	By grass and concrete or masonry drops	On grass part: 1.8 m/sec (6'/sec)	Overall slope <20° (36%)	For 4-wheel mechanization and in the middle of bench terraces
6. Waterway and road ditch complex	Parabolic	By grass and stone ballasting	3 m/sec (10'/sec)	<8° (14%)	For tractor crossing and 4-wheel mechanization
7. Foot-path and chute complex	Trapezoid or rectangular	By concrete or masonry structure	-	>20° (36%)	For paths on small farms and on very steep slopes

1/ These limits are approximations for general reference. In practice, the volume and velocity of runoff and site conditions should all be taken into consideration for determining the type of waterway needed. Most of these types of waterways handle a few hectares of runoff. (See Figure 8)

Table 6

TOTAL AND ANNUAL COSTS OF BENCH TERRACING
PER ACRE OF PRIVATE AND PUBLIC LANDS

Cutting 15ft (4.6 m) wide benches on 13° (23%) slope:

	Hand made	Machine built
Net Area	0.80	0.74
Volume to be cut and filled	798 cu.yds	785 cu.yds

	Hand made (Private Land)	Machine built (Public Land)
A. Terracing:		
1. Construction	(177 m/d x $2.00) 1/ J$354.00 2/	(16.2 hrs x $10.00) J$162.00
2. Riser stabi: ation	(2 m/d x J$2.00) 4.00	(10 m/d x J$2.33) 1/ 23.30
3. Soil fertility improvement	(50.00) (optional)	(100.00) (optional)
Sub-total	358.00 (408.00)	185.30 (285.30)
B. Waterway and Road:		
1. Waterway	80.00	130.00
2. Road	-	71.70
Sub-total	80.00	201.70
TOTAL COST	J$438.00	J$387.00
C. Interest and Amortization 3/	35.30	31.20
D. Annual Maintenance	(15 m/d x $2.00) 30.00	(15 m/d x $2.33) 35.00
TOTAL ANNUAL COST	J$65.30	J$66.20
(With soil fertility improvement)	(J$69.30)	(J$74.30)

1/ Wages for private land are J$2.00 per man-day and for public land J$2.33.

2/ J$1.00 equals US$1.10.

3/ 30 years amortization and 7% rate of interest.

XII.

GULLY CONTROL STRUCTURES AND SYSTEMS

by

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1. INTRODUCTION

1.1 The Main Processes of Gully Erosion

The mechanics of gully erosion can be reduced to two main processes: down cutting and head cutting. Down cutting of the gully bottom leads to gully deepening and widening. Head cutting extends the channel into ungullied headwater areas, and increases the stream net and its density by developing tributaries. Thus, effective gully control must stabilize both the channel gradient and channel headcuts.

1.2 Long-term Objective of Controls: Vegetation

In gully control, it is of benefit to recognize long- and short-term objectives because often it is very difficult or impossible to reach directly the long-term goal vegetation, and gully conditions must be first altered. Required alterations represent immediate objectives.

Where an effective vegetation cover will grow, gradients may be controlled by the establishment of plants without supplemental mechanical measures. Only rarely can vegetation alone stabilize headcuts, however, because of the concentrated forces of flow at these locations. The most effective cover in gullies is characterized by great plant density, deep and dense root systems, and low plant height. Although quantitative values cannot be given, it is obvious to the casual observer that a low, dense cover with dense, deep roots adds stability to the soil surface. Long, flexible plants, on the other hand, such as certain tall grasses, lie down on the gully bottom under the impact of flow. They provide a smooth interface between flow and original bed, and may substantially increase flow velocities. These higher velocities may endanger meandering gully banks and, in spite of bottom protection, widen the gully. Trees, especially if grown beyond sapling stage, may restrict the flow and cause diversion against the bank. Where such restrictions are concentrated, the flows may leave the gully. This is very undesirable because, in many cases, new gullies develop and new headcuts form where the flow re-enters the original channel.

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1.3 Engineers' Measures - an Aid to Vegetation Recovery

If growing conditions do not permit the direct establishment of vegetation (due to climatic or site restrictions, or to severity of gully erosion) engineering measures will be required. These measures are nearly always required at the critical locations where channel changes invariably take place. Examples are nickpoints on the gully bed, headcuts, and gully reaches close to gully mouth where deepening, widening, and deposition alternate frequently with different flows. Nickpoints signify longitudinal gradient changes; a gentler gradient is being extended toward headwaters by headcutting on the bed. Normally, critical locations are easily definable since the active stage of erosion at these sites leaves bed and banks in a raw, disturbed condition.

The designer must keep in mind that well-established vegetation perpetuates itself and thus represents a permanent type of control. In contrast, engineering measures always require some degree of maintenance. Because maintenance costs time and money, projects should be planned so that maintenance is not required indefinitely.

An effective engineering design must help establish and rehabilitate vegetation. Revegetation of a site can be aided in different ways. If the gully gradient is stabilized, vegetation can become established on the bed. Stabilized gully bottoms will make possible the stabilization of banks, since the toe of the gully side slopes is at rest. This process can be speeded up mechanically by sloughing gully banks where steep banks would prevent vegetation establishment. But sloughing should be done only after the bottom is stable. Vegetation rehabilitation is also speeded if large and deep deposits of sediment accumulate in the gully above engineering works. Such alluvial deposits make excellent aquifers, increase channel storage capacity, decrease channel gradients, and thus, decrease peak flows. Channel deposits may also raise the water table on the land outside the gully. They may reactivate dried-up springs, or may convert ephemeral springs to perennial flow. All these results create conditions much more favourable to plant growth than existing before control.

1.4 Watershed Restoration Aids Gully Control Measures

Measures taken outside the channel can also aid revegetation processes in the gully. Improvements on the watershed that increase infiltration and decrease overland flow, and spread instead of concentrate this flow, will benefit gully healing processes. Normally, however, improvements can be attained quicker within the gully than outside, because of concentration of treatment and availability of higher soil moisture in the defined channel.

Many types of watershed restoration measures have been devised. Since these are only supplemental to gully control, some examples will suffice here: seeding and planting with and without land preparation and fertilization; vegetation cover conversions; and engineering works such as reservoirs, water diversions, benches, terraces, trenches, and furrows.

1.5 Immediate Objectives of Control

The discussion on engineering works - vegetation cover relations in gully control - showed that different types of measures benefit plants in different ways. It is therefore important to clarify the type of help vegetation establishment requires most. Questions should be answered such as: is the present moisture regime of the gully bottom sufficient to support plants, or should the bottom be raised to increase moisture availability? One must recognize that a continuous, even raising of the bottom is not possible. Due to the processes of sedimentation above check dams, deposits have a wedge-shaped cross section if plotted along the thalweg.

The immediate objectives of a gully treatment must consider other aspects in addition to plant cover. Usually, these considerations involve hydraulics, sedimentation, soils, and sometimes the logistics required for the management of the watershed. For instance, management may call for deposits of maximum possible depth at strategic locations to provide shallow gully crossings. To achieve this objective will require the largest possible sediment accumulations. Thus, if sediment catch is a desirable objective, large dams should be built. But if esthetic considerations make check dams undesirable (and watershed logistics and revegetation offer no problems) gully bottom may be stabilized with dams submerged into the bed, and thus invisible to the casual observer. These examples illustrate how important it is to clarify the immediate and overall objectives of a planned treatment before deciding on approaches and measures. The objectives determine the measures; the measures determine the type of result.

2. TYPES OF POROUS CHECK DAMS

The most commonly applied engineering measure is the check dam. Forces acting on a check dam depend on design and type of construction material. Non-porous dams with no weep holes, such as those built from concrete, steel sheet, wet masonry and fibreglass, receive a strong impact from the dynamic and hydrostatic forces of the flow. These forces require strong anchoring of the dam into the gully banks, to which much of the pressure is transmitted. In contrast, porous dams release part of the flow through the structure, and thereby decrease the head of flow over the spillway and the dynamic and hydrostatic forces against the dam. Much less pressure is received at the banks than at non-porous dams. Since gullies, generally, are eroded from relatively soft soils, it is easier to design effective porous check dams than non-porous ones. Once the catch basin of porous or non-porous dams is filled by sediment deposits, however, structural stability is less critical because the dam crest has become a new level of the upstream gully floor.

Loose rock can be used in different types of check dams. Dams may be built of loose rock only, or the rock may be reinforced by wire mesh, steel posts, or other materials. The reinforcements may influence rock size requirements. If wire mesh with small mesh opening is used, rocks could be smaller than otherwise required by the design flow.

Some different types of check dams will be described, but the field of check dam design is wide open. Many variations are possible. Some of the most effective and inexpensive dams are built mainly from loose rock. They will, therefore, be emphasized in the descriptions that follow.

2.1 Loose Rock

The basic design of a loose-rock check dam is illustrated in Figure 1. Volumes of excavation and of rocks required in the construction can be calculated from the drawings given in this paper. Rock volumes can also be obtained from an equation discussed in the section on Equations for Volume Calculations. If facilities are available to use the computer programme developed by Heede and Mufich (1974), volumes also may be calculated by computer. In a Colorado project, the drawings also served well in the field as construction plans (3).

Since loose-rock dams are not reinforced, the angle of rest of the rock should determine the slopes of the dam sides. This angle depends on the type of rock, the weight, size, and shape of the individual rocks, and their size distribution. If the dam sides are constructed at an angle steeper than that of rest, the structure will be unstable and may lose its shape during the first heavy runoff. For the design of check dams, the following rule of thumb can be used:

> the angle of rest for angular rock corresponds to a slope ratio of 1.25 to 1.00; for round rock, 1.50 to 1.00. Figure 2 illustrates a dam built from angular loose rock

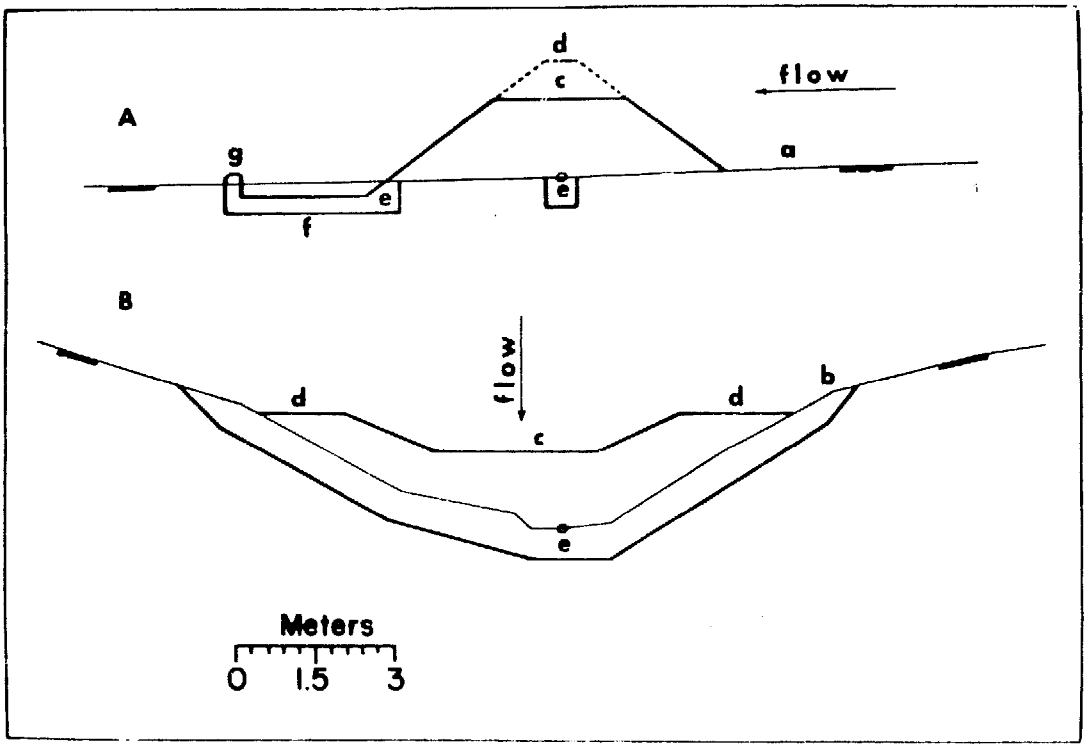

Figure 1. Construction plans for a loose-rock check dam

A. Section of the dam parallel to the centreline of the gully.

B. Section of the dam at the cross section of the gully.

a = original gully bottom; b = original gully cross section;

c = spillway; d = crest of free board; e = excavation for key;

f = excavation for apron; g = end sill.

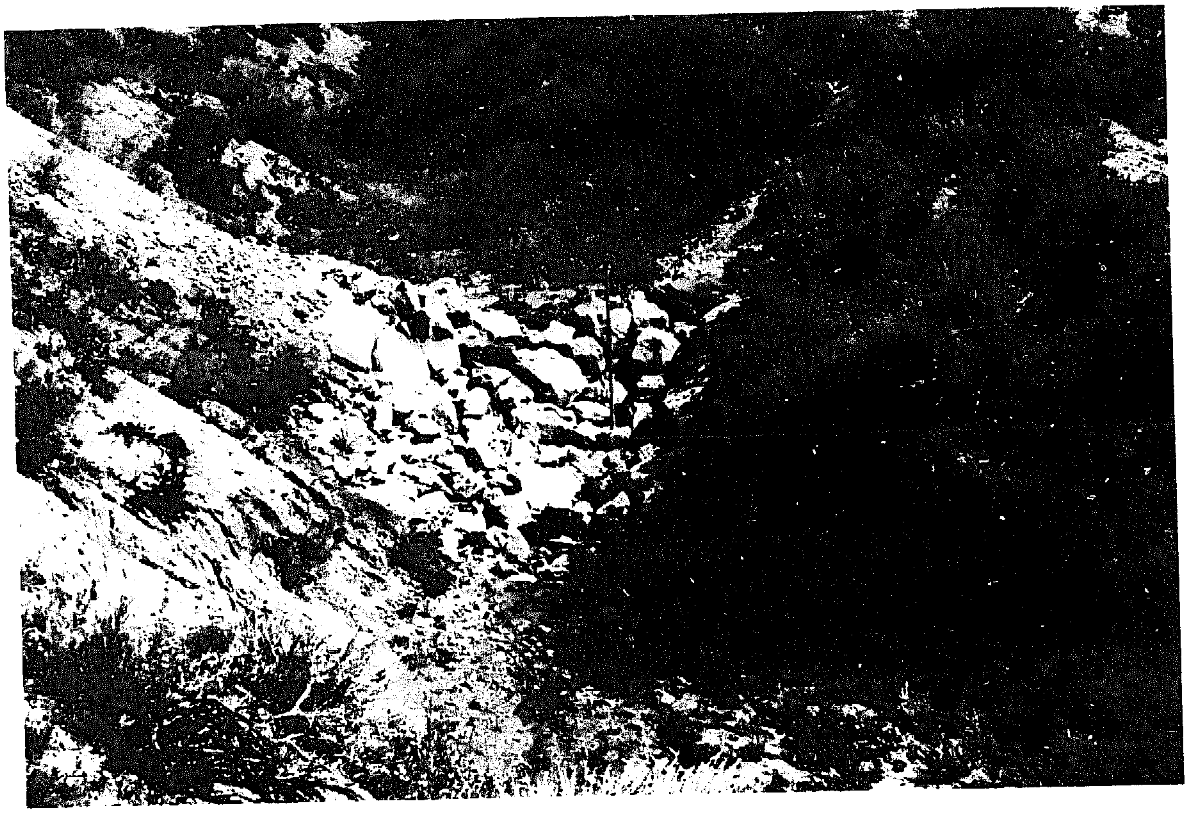

Figure 2. Upstream view of loose-rock check dam. Catchment basin of dam has filled with sediment during the first spring runoff after construction. Rod is 1.7 m high.

2.2 Wire-bound Loose Rock

A wire-bound check dam is identical in shape to that of a loose-rock dam, but the loose rock is enclosed in wire mesh to reinforce the structure. The flexibility within the wire mesh is sufficient to permit adjustments in the structural shape, if the dam sides are not initially sloped to the angle of rest. Therefore, the same rock design criteria are required for a wire-bound dam as for a loose-rock structure.

The wire mesh should: (1) be resistant to corrosion, (2) be of sufficient strength to withstand the pressure exerted by flow and rocks, and (3) have openings not larger than the average rock size in the dam. Wire mesh may not be effective in boulder-strewn gullies supporting flows with heavy, coarse loads.

2.3 Single Fence

Single-fence rock check dams (Figure 3) differ greatly in shape and requirements of construction materials from the loose-rock and wire-bound dams. These structures consist of a wire-mesh fence, fastened to steel posts and strung at right angles across the gully, and a loose-rock fill, piled from upstream against the fence. The rock fill can be constructed at an angle steeper than that of rest for two reasons:

1. The impact of flows will tend to push the individual rock into the fill and against the dam.

2. Sediment deposits will add stability to the fill and will eventually cover it.

The design of this type of check dam should emphasize specifications for the wire mesh, and the setting, spacing, and securing of the steel posts. The wire mesh specifications will be the same as those for the wire-bound dams.

The steel posts should be sufficiently strong to resist the pressure of the rock fill and the flows. They must be driven into the gully bottom and side slopes to a depth that insures their stability in saturated soil. If it is impractical to drive posts to sufficient depths, the stability of the posts should be enhanced by guys. These guys should be anchored to other posts that will be covered and thus held in place by the rock fill.

> In general, the fenceposts should not be spaced more than 1.2 m to prevent excessive pouching (stretching) of the wire mesh. Where conditions do not allow this spacing, a maximum of 1.5 m can be used but the fence must be reinforced by steel posts fastened horizontally between the vertical posts.

Excessive pouching of the wire mesh reduces the structural height and impairs the stability of the dam. Figure 4 shows a single-fence dam at time of finish of construction.

2.4 Double Fence

The double-fence rock check dam has two wire mesh fences, strung at a distance from each other across the channel (Figure 5). In this type of dam, a well graded supply of rocks is essential, otherwise the relative thinness of the structure would permit rapid throughflow, resulting in water jets. Double-fence dams should only be built if an effective rock gradation can be obtained.

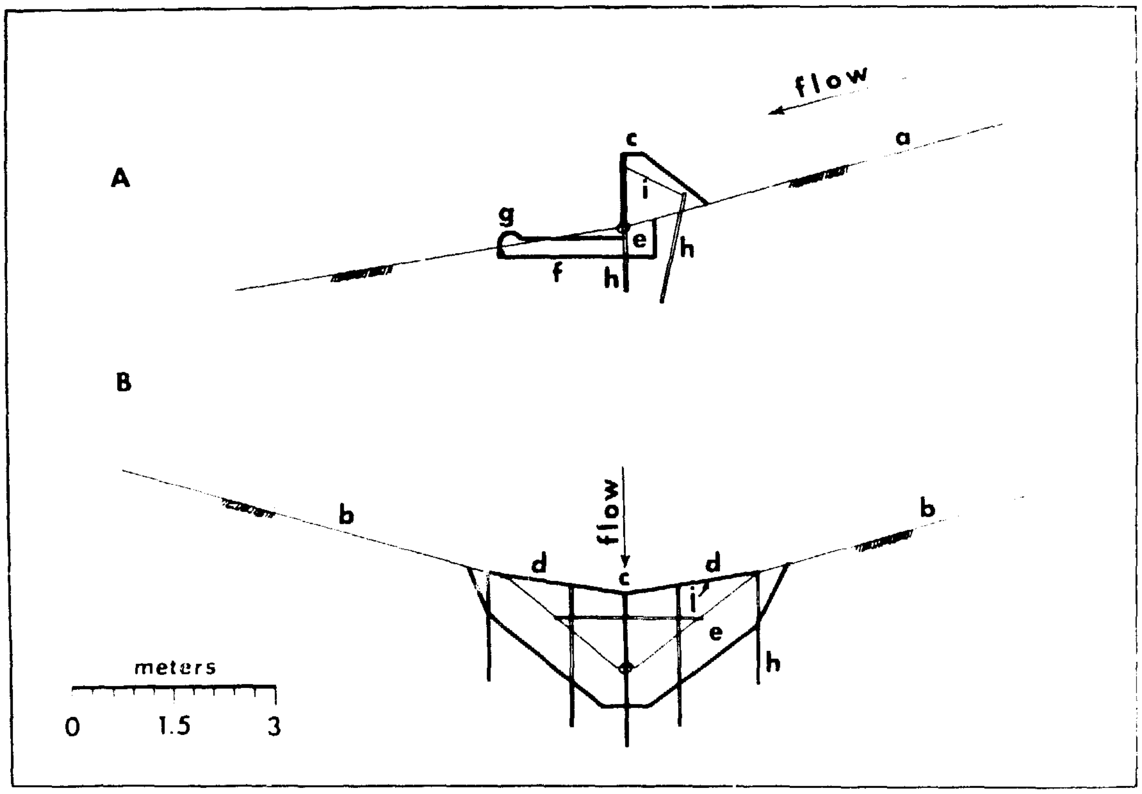

Figure 3. The construction plans for the single-fence rock check dam

A. Section of the dam parallel to the centreline of the gully.

B. Section of the dam at the cross section of the gully.

a = original gully bottom; b = original gully cross section;
c = spillway; d = crest of free board; e = excavation for key;
f = excavation for apron; g = end sill; h = steel fencepost;
k = guys; j = rebar, 13 mm in diameter.

Figure 4. Looking across a single-fence dam. Apron and gully bank protection is to the left of dam crest.

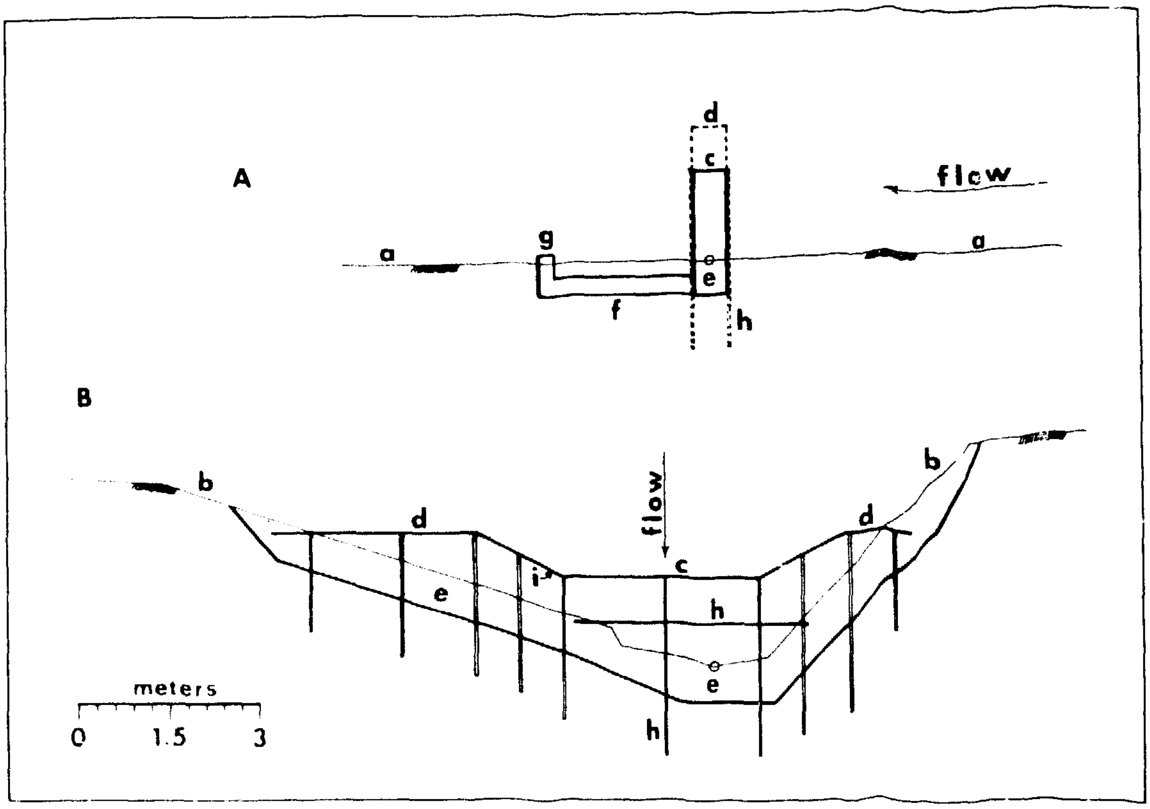

Figure 5. The construction plans for the double-fence rock check dam

A. Section of the dam parallel to the centreline of the gully.

B. Section of the dam at the cross section of the gully.

a = original gully bottom; b = original gully cross section;

c = spillway; d = crest of free board; e = excavation for key;

f = excavation for apron; g = end sill; h = steel fencepost;

i = rebar, 13 mm in diameter.

In Colorado (3) parallel fences were spaced 0.6 m. Peak flows did not exceed 0.7 m^3/s and loads consisted mainly of finer material. Dams were no taller than 1.8 m (Figure 6). At many dam sites, maintenance and repairs were required because excessive water jetting through the structures caused bank damage. The percentage of small rock sizes was too low.

When flows of large magnitude, say 2 cubic metres per second (m^3/s), or gullies on steep hillsides are encountered, the base of the double-fence dam should be wider than the crest. This will add structural stability and increase the length of the flow through the lower part of the dam.

2.5 Gabion

A gabion check dam consists of prefabricated wire cages that are filled with loose rock. Individual cages are placed beside and onto each other to obtain the dam shape. Normally, this dam is more esthetically pleasing, but it is more costly than loose-rock or wire-bound rock check dams.

2.6 Head Cut Control

Head cuts can be stabilized by different types of structures, but all have two important requirements: (1) porosity in order to avoid excessive pressures and thus eliminate the need for large, heavy structural foundations, and (2) some type of inverted filter that leads the seepage gradually from smaller to the larger openings in the structure. Otherwise, the soils will be carried through the control, resulting in erosion. An inverted filter can be obtained if the head cut wall is sloughed to such an angle that material can be placed in layers of increasing particle size, from fine to coarse sand and on to fine and coarse gravel. Good results may also be obtained by use of erosion cloth, a plastic sheet available in two degrees of porosity.

If rock walls reinforced by wire mesh and steel posts are used, site preparation can be minimized. Loose rock can be an effective head cut control (3) if the flow through the structure is controlled also. As in loose-rock check dams, the size, shape, and size distribution of the rock are of special importance to the success of the structure. The wall of the head cut must be sloped back so the rock can be placed against it.

If the toe of the rock fill should be eroded away, the fill would be lost. Therefore, stabilization of this toe must be emphasized in the design. A loose-rock dam can be designed to dissipate energy from the chuting flows, and to catch sediment (Figure 7). Sediment depositions will further stabilize the toe of the rock fill by encouraging vegetation during periods with no or low channel flow.

3. GENERAL DESIGN CRITERIA

3.1 Loose Rock

Loose rock has proved to be a very suitable construction material if used correctly. Often it is found on the land and thus eliminates expenditures for long hauls. Machine and/or hand labour may be used. The quality, shape, size and size distribution of the rock used in construction of a check dam affect the success and life span of the structure. Obviously, rock that disintegrates rapidly when exposed to water and atmosphere will have a short structural life. Further, if only small rocks are used in a dam, they may be moved by the impact of the first large water flow, and the dam quickly destroyed. In contrast, a check dam constructed of large rocks that leave large voids in the structure will offer resistance to the flow, but may create water jets through the voids. These jets can be highly destructive if directed toward openings in the bank protection work or other unprotected parts of the channel. Large voids in check dams also prevent the accumulation of sediment above the structures. In general, this accumulation is desirable because it increases the stability of structures and enhances stabilization of the gully.

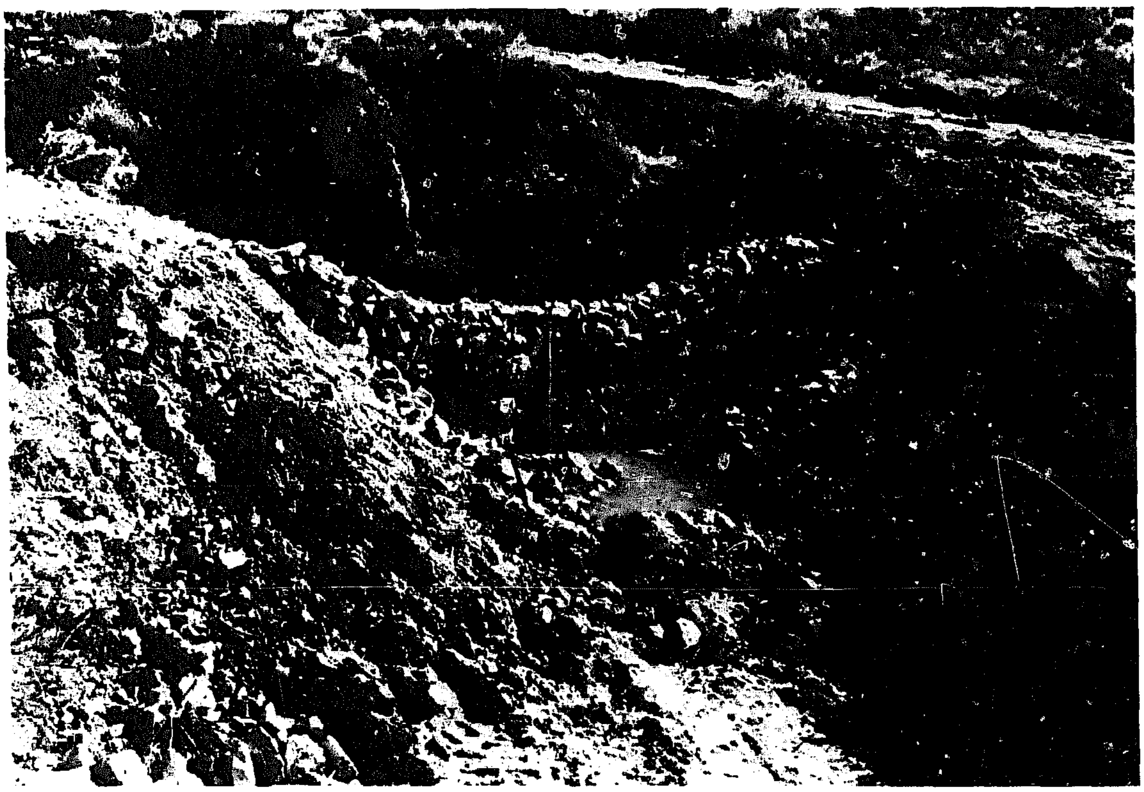

Figure 6. Upstream view of a double-fence dam. Note the bank protection work. The apron is covered by water. Length of rod is 1.7 m.

Large voids will be avoided if the rock is well graded. Well-graded rock will permit some flow through the structure. The majority of the rock should be large enough to resist the flow.

Since required size and gradation of rock depend on size of dam and magnitude of flow, strict rules for effective rock gradation cannot be given. The recommendations given below are empirical values derived from gully treatments in the Colorado Rocky Mountains and should be evaluated accordingly. The designer should use these values only as a basis for his decision in his own area. As a general rule, however, rock diameters should not be less than 10 centimetres (cm) and 25 percent of all rocks should fall into the 10 to 14 cm size class. The upper size limit will be determined by the size of the dam; large dams can include larger rock than small ones. Flat and round rock, such as river material, should be avoided. Both types slip out of a structure more easily than broken rocks, which anchor well with each other. In general, large design peak flows will require larger rock sizes than small flows. As an example, assume that the designed total dam height ranges between 1 and 2 metres (m), where total height is measured from the bottom of the dam to the crest of the free board. Type of dam is loose rock without reinforcement. Design peak flow is estimated not to exceed 1 cubic metre per second (m^3/s). An effective rock gradation would call for a distribution of size classes as follows:

10 - 14 cm,	25 percent
15 - 19 cm,	20 percent
20 - 30 cm,	25 percent
31 - 45 cm,	30 percent

If on the other hand, dam height would be increased to 3 m, rock up to 1 m diameter, constituting 15 percent of the volume could be placed into the basis of the dam and the second size class decreased by this portion; or if peak flow was estimated not to exceed 0.75 m^3/s, the 31-45 cm size class could be eliminated and 55 percent of the volume could be in the 20-30 cm class.

In ephemeral gullies, only in exceptional cases will meaningful flow information be available that permits a realistic estimate of average velocities at the structural sites. If so, a formula developed by Isbach and quoted by Leliavsky (8), may be used to check the suitability of the larger sizes as given by the gradation approach. The equation relates the weight of rock (W) to the mean velocity of the flow (V) as follows:

$$W = 2.44 \times 10^{-5} V^6$$

where W is the weight of rock related to D_{65} of the rocks. D_{65} is the sieve size in the material of which 65 percent are finer. This formula states that 65 percent of the rocks can be smaller and 35 percent larger than the calculated weight. As stated above, the possible smallest size should have a diameter of 10 cm.

3.2 Spacing

The location of a check dam will be determined primarily from the required spacing of the structures. Requirements for spacing depend on the gradients of the sediment deposits expected to accumulate above the dams, the effective heights of the dams, the available funds, and the objective of the gully treatment. If, for instance, the objective is to achieve the greatest possible deposition of sediment, then widely spaced, high dams would be constructed. On the other hand, if the objective is mainly to stabilize the gully gradient, then the spacing would be relatively close and the dams low.

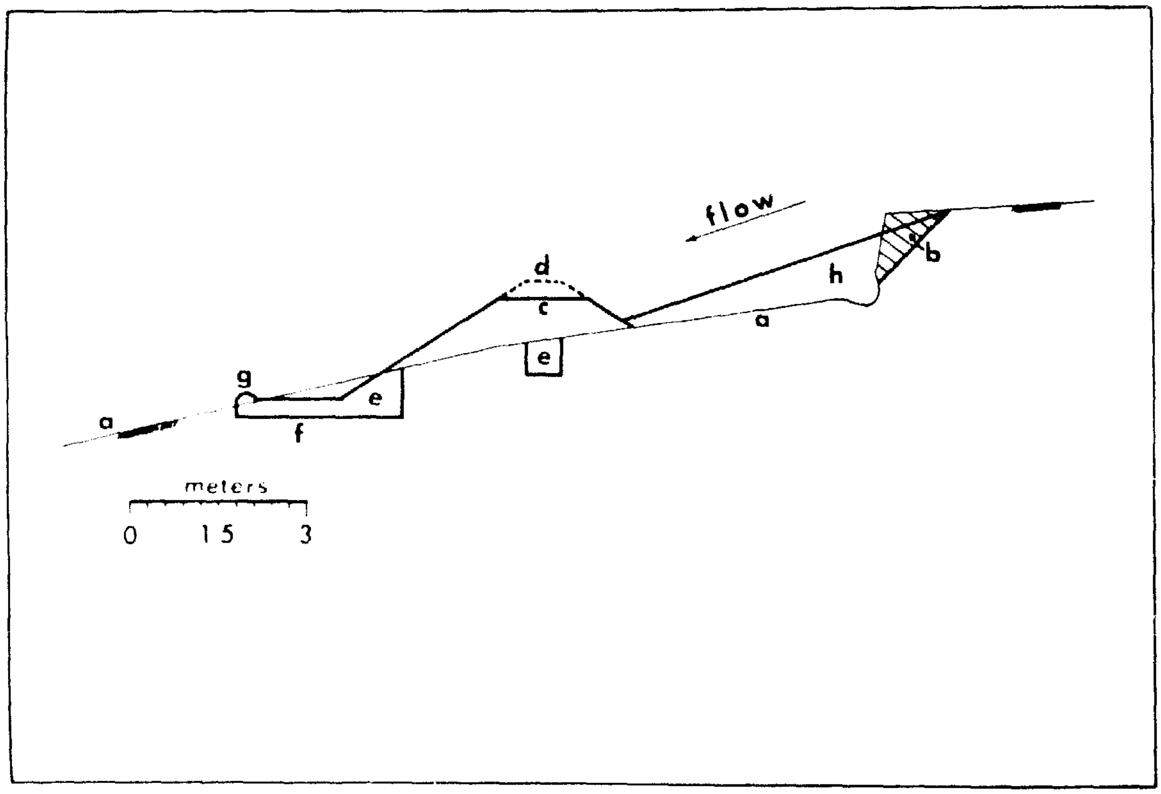

Figure 7. The construction plan of the gully head cut control with a loose-rock check dam. The section of the structures is illustrated parallel to the centreline of the gully.

a - original gully bottom; b - excavated area of head cut wall;

c - spillway; d - crest of free board; e - excavation for key;

f - excavation for apron; g - end sill; h - rock fill.

In general, the most efficient and most economical spacing is obtained if a check dam is placed at the upstream toe of the final sediment deposits of the next dam downstream. This ideal spacing can only be estimated, of course, to obtain guidelines for construction plans.

Normally, objectives of gully control require spacings of check dams great enough to allow the full utilization of the sediment-holding capacity of the structures. To determine this spacing requires definite knowledge of the relationship between the original gradient of gully channels and that of sediment deposits above check dams placed in these gullies. This relationship has been hypothesized by several authors. Others demonstrated that not only the original channel gradient influences the deposition slope, but also the width of the channel at the structure and the height of crest of spillway above the original channel bottom. Relationships developed so far have been entirely empirical, and further research is necessary to establish the theoretical basis.

In Colorado, earth dams were examined for guidance in determining the spacing of dams (3). Data indicated that, in gullies of less than 20 percent gradient, the dams would not interfere with sediment catch if their spacing was based on the expected slope of the deposits being 0.7 of the original gully gradient. For gully gradients exceeding 20 percent, expected sediment deposits would have a gradient of 0.5 that of the gully. Heede and Mufich (6) developed a formula to ease the calculation of spacing as follows:

$$S = \frac{H_E}{K\,G\,\cos a} \qquad (1)$$

where S is the spacing, H_E is effective dam height as measured from gully bottom to spillway crest, G represents the gully gradient as a ratio, a is the angle corresponding to the gully gradient ($G = \tan a$), and K is a constant. The equation is based on the assumption that the gradient of the sediment deposits is $(1-K)G$. In the Colorado example, values for K were as follows:

$$K = 0.3 \text{ for } G \leq 0.20 \qquad (2)$$

$$K = 0.5 \text{ for } G > 0.20 \qquad (3)$$

The generalized formula (1) can be used by the designer, after the applicable K value has been determined for the treatment area. Works older than 10 years should be inspected for this determination. Figure 8 illustrates the relationship between dam spacing, height and gully gradient. For a given gully, the required number of dams decreases with increasing spacing or increasing effective dam height, and increases with increasing gully gradient. An example for a 2 000 feet (609 m) gully segment is given in Figure 9.

3.3 Keys

Keying a check dam into the side slopes and bottom of the gully greatly enhances the stability of the structure. Such keying is important in gullies where expected peak flow is large, and where soils are highly erosive (such as soils with high sand content). Loose rock check dams without keys were successfully installed in soils derived from Pikes Peak granite, but estimated peak flows did not exceed 0.2 m^3/s, Heede (1).

The objective of extending the key into the gully side slopes is to prevent destructive flows of water around the dam and consequent scouring of the banks. Scouring could lead to gaps between dam and bank that would render the structure ineffective. The keys minimize the danger of scouring and tunnelling around check dams because the route of seepage is considerably lengthened. As voids in the key become plugged, the length of the seepage route increases. This increase causes a decrease in the flow velocity of the seepage water and, in turn, a decrease of the erosion energy.

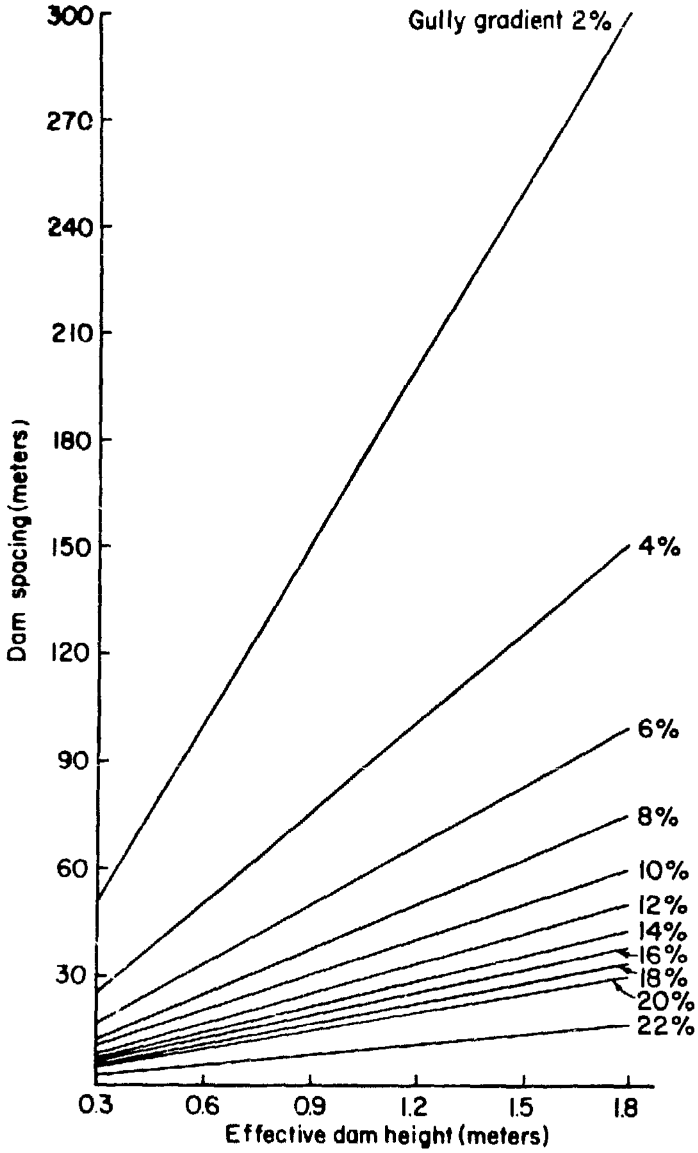

Figure 8. Spacing of check dams, installed in gullies with different gradients, as a function of effective dam height.

The part of the key placed into the gully bottom is designed to safeguard the check dam against undercutting at the downstream side. Therefore, the base of the key, which constitutes the footing of the dam, must be designed to be below the surface of the apron. This is of particular importance for fence-type and impervious structures because of the greater danger of scouring at the foot of these dams. The water flowing over the spillway forms a chute that creates a main critical area of impact where the hydraulic jump strikes the gully bottom. This location is away from the structure. The sides of loose-rock and wire-bound check dams slope onto the apron, on the other hand, and no freefall of water occurs.

The design of the keys calls for a trench, usually 0.6 m deep and wide, dug across the channel. Where excessive instability is demonstrated by large amounts of loose materials on the lower part of the channel side slopes or by large cracks and fissures in the bank walls, the depth of the trench should be increased to 1.2 or 1.8 metres.

Dam construction starts with the filling of the key with loose rock. Then the dam is erected on the rock fill. Rock size distribution in the keys should be watched carefully. If voids in the keys are large, velocities of flow within the key may lead to washouts of the bank materials. Since the rock of the keys is embedded in the trench and therefore cannot be easily moved, it is advantageous to use smaller materials, such as a mixture with 80 percent smaller than 14 cm.

3.4 Height

The effective height of a check dam (H_E) is the elevation of the crest of the spillway above the original gully bottom. The height not only influences structural spacing but also volume of sediment deposits.

Heede and Mufich (6) developed a formula that relates the volume of sediment deposits to spacing and effective height of dam:

$$V_S = 1/2\ H_E\ S \cos a\ L_{HE} \qquad (4)$$

where V_S is the sediment volume, S represents the spacing, and L_{HE} is the average length of dam, considered for effective dam height and calculated by the equation:

$$L_{HE} = L_B + \frac{L_U - L_B}{2D} H_E \qquad (5)$$

where L_B is the bottom width and L_U the bank width of the gully, measured from brink to brink, and D is the depth of the gully. If S in equation (4) is substituted, then

$$V_S = \frac{H_E^2}{2KG} L_{HE} \qquad (6)$$

where the constant K has the values found to be applicable to the treatment area. Equation (6) indicates that sediment deposits increase as the square of effective dam height. This is illustrated in Figure 10.

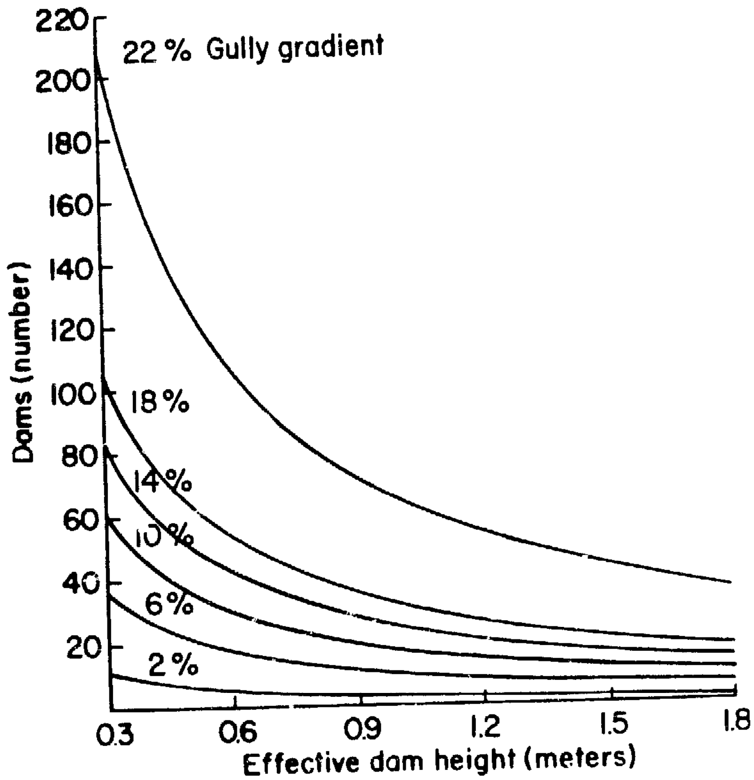

Figure 9. Number of dams required in gullies, 600 m long and with different gradients, as a function of effective dam height.

For practical purposes, based on the sediment deposit model, the sediment curve in Figure 10 is valid for treatments in gullies with identiccal cross sections and gradients ranging from 1 to 30 percent. At this range, the difference is 4.5 percent with smaller deposits on the steeper gradients, a negligible fraction in such estimates. The volume of deposits, compared with that on a 1 percent gradient, decreases by 10 percent on a gradient of 45 percent, if the cross sections are constant. Magnitudes of cross sections, of course, exert strong influences on sediment deposition.

In most cases, dam height will be restricted by one or all of the following criteria: (1) costs, (2) stability and (3) channel geometry in relation to spillway requirements. Cost relations between different types of rock check dams will be discussed later. Stability of impervious check dams should be calculated where life and/or property would be endangered by failure. Heede (2) presented an example for these calculations which can be easily followed. Pervious dams such as rock check dams cannot be easily analysed for stability because of unknowns such as the porosity of a structure.

Severely tested check dams in Colorado (3) had maximum heights as follows: loose-rock and wire-bound dams, 2.2 m, and fence-type dams (thickness of 0.6 m) 1.8 m.

In gullies with small widths and depths but large magnitudes of flow, the effective height of dams may be greatly restricted by the spillway requirements. This restriction may result from the spillway depth necessary to accommodate expected debris-laden flows.

3.5 Spillway

Since spillways of rock check dams may be considered broad-crested weirs, the discharge formula for that type of weir is applicable:

$$Q = CLH^{3/2} \qquad (7)$$

where Q = discharge in m^3/s

C = coefficient of the weir

L = effective length of the weir in m, and

H = head of flow above the weir crest in m

The value of C varies. The exact value depends on the roughness as well as the breath and shape of the weir and the depth of flow. Since in rock check dams, breadth of weir changes within a structure from one spillway side to the other, and shape and roughness of the rocks lining the spillway also change, C would have to be determined experimentally for each dam. This, of course, is not practical and it is recommended, therefore, to use a mean value of 1.65. This value appears reasonable in the light of other inaccuracies that are introduced in calculating the design storm and its expected peak flow. For this reason also, the discharge calculations would not be significantly improved if they were corrected for velocity of approach existing above a dam. Such a correction would amount to an increase of 5 percent of the calculated discharge at a head of flow of 0.6 m over a dam 0.75 m high, or 8 percent if the flow had a 0.9 m head.

Most gullies have either trapezoidal, rectangular, or V-shaped cross sections. Heede and Mufich (7) developed formulas for the calculation of spillway dimensions for check dams placed into differently shaped gullies. In trapezoidal gullies, the formula for length of spillway can be adjusted to prevent the water overfall from hitting the gully side slopes, thus eliminating the need for extensive bank protection. In V-shaped gullies this is not possible, generally. In rectangular ones, adjustment of the formula is not required because the free-board requirement prevents the water falling directly on the banks. One formula was

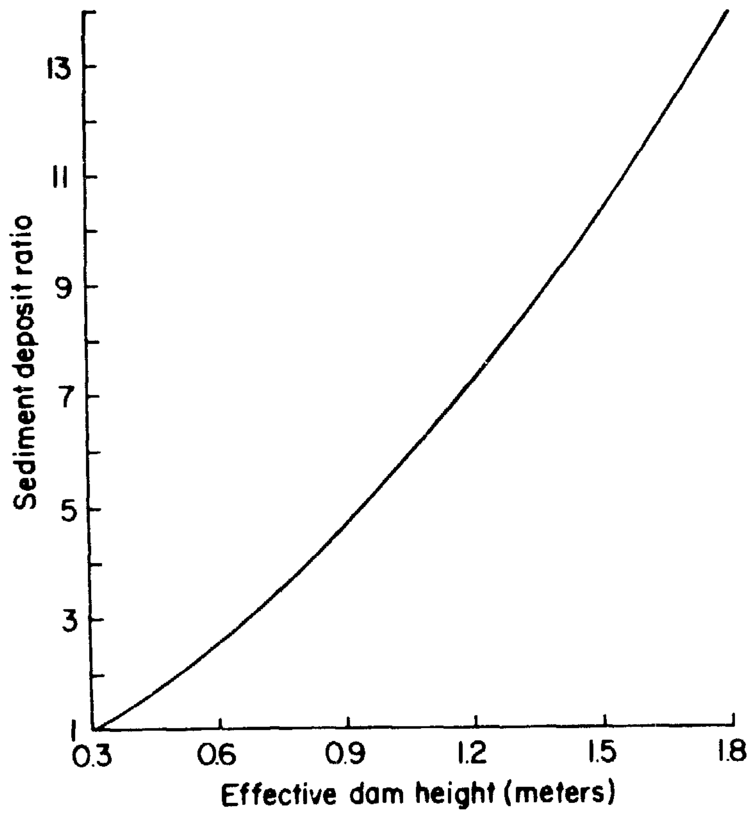

Figure 10. Expected sediment deposits retained by check dam treatment as a function of effective dam height. The sediment deposit ratio relates the volume of sediment deposits to the volume of sediment deposits at effective dam height of 0.3 m. Thus, deposits in a treatment with 1.2 m dams are more than seven times larger than those caught by 0.3 m dams.

established, therefore, for V-shaped and rectangular gullies as follows:

$$H_{SV} = \left(\frac{Q}{CL_{AS}} \right)^{2/3} \tag{8}$$

where H_{SV} is spillway depth, the constant C is taken as 1.65, and L_{AS}, the effective length of spillway, was derived from the equation

$$L_{AS} = \frac{L_U}{D} H_E - f \tag{9}$$

in which f is a constant, referring to the length of the free board. In gullies with a depth of 1.5 m or less, the f value should not be less than 0.3 m; in gullies deeper than 1.5 m, the minimum value should at least be 0.6 m.

For structural gully control, design storms should be of 25 years magnitude, and, as a minimum spillways should accommodate the expected peak flow form such a storm. In mountainous watersheds, however, where forests and brushlands often contribute large amounts of debris to the flow, the size and the shape of spillways should be determined by this expected organic material. As a result, required spillway sizes will be much larger than if the flow could be considered alone. Spillways designed with great lengths relative to their depths are very important here. Yet, spillway length can be extended only within limits because a sufficient contraction of the flow over the spillway is needed to form larger depths of flows to float larger loads over the crest. The obstruction of a spillway by debris is undesirable since it may cause the flow to overtop the free board of the check dam and lead to its destruction.

The characteristics of the sides of a spillway are also important for the release of debris over the structure. Spillways with perpendicular sides will retain debris much easier than those with sloping sides; in other words trapezoidal cross sections are preferable to rectangular ones. A trapezoidal shape introduces another benefit by increasing the effective length of the spillway with increasing magnitudes of flow.

The length of the spillway relative to the width of the gully bottom is important for the protection of the channel and the structure. Normally, it is desirable to design spillways with a length not greater than the available gully bottom width so that the waterfall from the dam will strike the gully bottom. There, due to the stilling-basin effects of the dam apron, the turbulence of the flow is better controlled than if the water first strikes against the banks. Splashing of water against the channel side slopes should be kept at a minimum to prevent new erosion. Generally, spillway length will exceed gully bottom width in gullies with V-shaped cross sections, or where large flows of water and debris are expected relative to the available bottom width. In such cases, intensive protection of the gully side slopes below the structures is required.

Equation (9) includes a safety margin, because the effective length of the spillway is calculated with reference to the width of the gully at the elevation of the spillway bottom, instead of that at half the depth of the spillway. At spillway bottom elevation, gullies are generally narrower than at the location of the effective spillway length. This results in somewhat smaller spillway lengths, which will benefit the fit of the spillway into the dam and the gully.

If the spillway sides are sloped 1:1, it follows that in V-shaped and rectangular gullies, the bottom length of the spillway (L_{BSV}) is derived from the equation

$$L_{BSV} = L_{AS} - H_{SV} \tag{10}$$

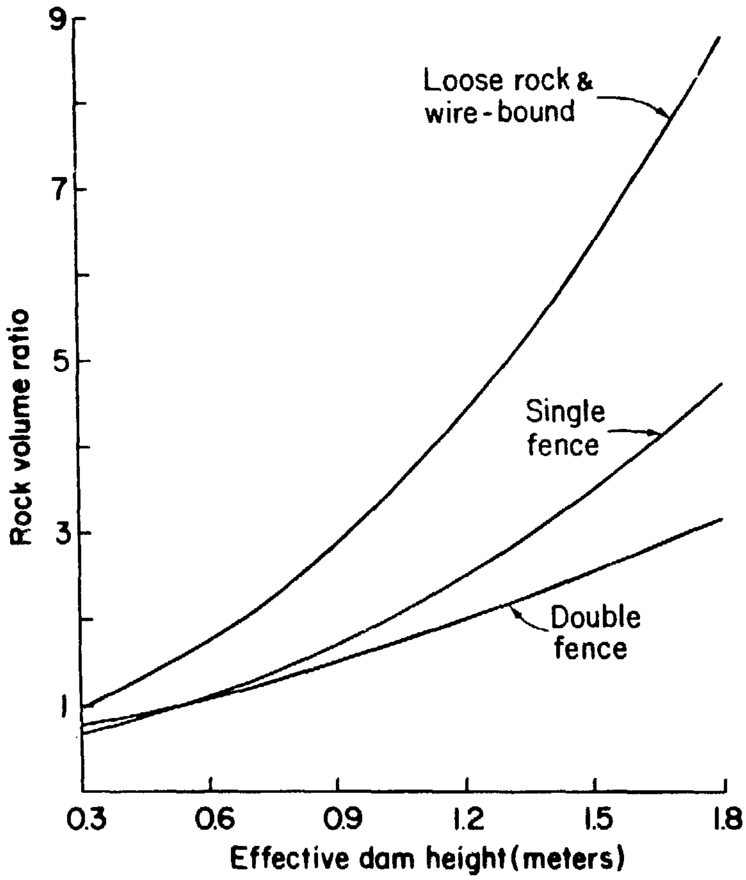

Figure 11. Required volumes of angular rock for four different dam types as a function of effective dam height. The rock volume ratio relates the rock volume to that of a loose-rock dam 0.3 m high.

and the length between the brinks of the spillway (L_{USV}) is given by the equation

$$L_{USV} = L_{AS} + H_{SV} \quad (11)$$

In trapezoidal gullies, the effective length of the spillway equals the bottom width of the gully. From the discharge formula for broad-crested weirs, it follows that the depth of spillway (H_S) in these gullies is given by the equation

$$H_S = \left(\frac{Q}{CL_B}\right)^{2/3} \quad (12)$$

in which the coefficient of the weir (C) is taken as 1.65.

Lengths at the bottom (L_{BS}) and between the brinks of the spillway (L_{US}) are calculated by the equations

$$L_{BS} = L_B - H_S \quad (13)$$

and

$$L_{US} = L_B + H_S \quad (14)$$

respectively.

3.6 Apron

Aprons must be installed on the gully bottom and protective works on the gully side slopes below the check dams, otherwise flows may easily undercut the structures from downstream and destroy them.

Without field and laboratory investigations on prototypes, apron length below a loose-rock check dam cannot be calculated. Different structures may have different roughness coefficients of the dam side slope that forms a chute to the flow if tailwater depth is low. Differences in rock gradation may be mainly responsible for the different roughness values.

The design procedures for the loose rock aprons were, therefore, simplified and a rule of thumb adopted: the length of the apron was taken as 1.5 times the height of the structure in channels where the gradient did not exceed 15 percent, and 1.75 times where the gradient was steeper than 15 percent. The resulting apron lengths included a sufficient margin of safety to prevent the waterfall from hitting the unprotected gully bottom. The design provided for embedding the apron into the channel floor so that its surface would be roughly level and about 0.15 m below the original bottom elevation.

In contrast, for straight-drop structures such as dams built from steel sheets or fence-type dams, apron length can be calculated if gully flows are known. In such a case, the trajectory of the nappe can be computed as follows:

$$V_o = x \sqrt{\frac{g}{2(-z)}} \quad (15)$$

Figure 12. Backhoe is excavating key for the installation of a loose-rock check dam.

Figure 13. Upstream view of construction site of wire-bound dam. Note that key and apron excavations were filled with rock before wire mesh was placed on the bed and banks. The site is prepared for the construction of the dam proper.

Figure 14. Parallel fences for double-fence dam are being installed. Note the excavations for key, apron, and bank protection, both of the latter to right of the structure.

in which x and z are the horizontal and vertical coordinates of a point on the trajectory referred to the midpoint of the spillway as the origin, and g is the acceleration due to gravity, taken as 9.81 m/s^2. Thus, if V_o is substituted for V_c, the critical velocity at dam crest, and z is the effective dam height, x will yield the distance from the structure at which the waterfall will hit the apron. Depending on magnitude of flow, one or several metres should be added to this distance.

For calculating critical depth and critical velocity over a check dam, the procedure can be used as follows: the critical depth formula is

$$\frac{V_c^2}{2g} = \frac{Y_c}{2} \qquad (16)$$

where V_c is the critical velocity. Y_c is the critical depth. The continuity equation for open channel flow is

$$q = AV \qquad (17)$$

where q is the flow rate of unit width of flow, A is the cross section of flow and V represents the average velocity in the cross section. q is derived from the estimated rate of flow (Q) by dividing (Q) by (L_{AS}), the effective length of spillway. Since q refers to unit width of flow, A can be substituted by Y_c and equation (17) becomes

$$V_c = \frac{q}{Y_c} \qquad (18)$$

If V_c in equation (16) is substituted by (18),

$$\frac{q^2}{g} = Y_c^3 \qquad (19)$$

By placing the value of Y_c into equation (18), the critical velocity (V_c) can be obtained.

At the downstream end of the apron, a loose rock sill should be built 0.15 m high, measured from channel bottom elevation to the crest of the sill. This end sill creates a pool in which the water will cushion the impact of the waterfall.

The installation of an end sill provides another benefit for the structure. Generally, aprons are endangered by the so-called ground roller that develops where the hydraulic jump of the water hits the gully bottom. These vertical ground rollers of the flow rotate upstream, and where they strike the gully floor, scouring takes place. Thus, if the hydraulic jump is close to the apron, the ground roller may undermine the apron and destroy it. The end sill will shift the hydraulic jump farther downstream, and with it the dangerous ground roller. The higher the end sill, the farther downstream the jump will occur. Since data on sediment and flow are not usually available, a uniform height of sill may be used for all structures.

Ephemeral gullies carry frequent flows of small magnitudes. Therefore, it is advisable not to raise the crest of the end sills more than 0.15 to 0.25 m above the gully bottom. End sills, if not submerged by the water, are dams and create waterfalls that may scour the ground below the sill. At higher flows, some tailwater usually exists below a sill and cushions to some extent the impact from the waterfall over the sill.

Where the downstream nature of the gully is such that appreciable depth of tailwater is expected, the installation of end sills is not critically important. The hydraulic jump will strike the water surface and ground rollers will be weak.

where L_B is the length of dam at the bottom, L_U represents the length of dam measured at free board elevation, and D is the depth of the gully. V_{SP} is calculated by the equation

$$V_{SP} = H_S \times L_{AS} \times B_A \qquad (22)$$

where H_S is the depth and L_{AS} is the effective length of the spillway, and B_A is the breadth of the dam, measured at half the depth of the spillway and derived from the formula

$$B_A = \frac{H_S}{0.70711 \tan A_R} + 0.3 \qquad (23)$$

where 0.70711 is the sine of 45^o, and 0.3 is a constant derived from a breadth of dam of 0.6 m.

Angular rock is preferable to round rock because less is required, and it enhances dam stability.

The equation for volumes of loose-rock and wire-bound loose-rock dams (20) was simplified by assuming a zero gully gradient. This assumption results in an underestimate of volumes in gullies with steep gradients. To offset this underestimate on gradients larger than 15 percent, 10 percent should be added to the calculated volume.

If the design peak flow is larger than 0.3 m^3/s, all types of check dams must be keyed into the gully banks and bottom. Under varied conditions in Colorado, it was found that a bottom key of 0.6 m depth and width was sufficient for check dams up to 2 m high. A width of 0.6 m was also adequate for the bank keys. The depth of the keys, however, must be adjusted according to characteristics of the soils. Thus, the equation for the volume of the key is generalized as follows:

$$V_K = (L_A + 2R)\ (0.6H_D + 0.36) - L_A\ 0.6H_D \qquad (24)$$

where R represents the depth of key and 0.6 and 0.36 are constants in metre units, referring to depth and width of bottom key and width of bank key, respectively.

In the construction plan, the volume V_K should be kept separate from that of the dam proper because, generally, a finer rock gradation is required for the keys.

Apron and bank protection below the structure are always required at check dams. The equation developed for the volume calculations is:

$$V_A = cH_DL_B + dH^2 \qquad (25)$$

in which V_A is the rock volume of the apron and bank protection, and c and d are constants whose values depend on gully gradient. For gradients $\leq$ 15 percent, c = 1.5 and d = 3.0; for gradients > 15 percent, c = 1.75 and d = 3.5.

The total rock volume required for a loose-rock dam with keys is the sum of equations (20), (24), and (25).

Besides rock, wire mesh and steel fenceposts are used in most of the dams. If dam height is equal to or larger than 1.2 m, reinforcement of the bank protection work by wire mesh and fenceposts will generally be required. The equation for amount of wire mesh and number of posts includes a margin of safety to offset unforseen additional needs. To assist in construction, dimensions of the mesh are given in length and width. The length measured

3.7 Bank Protection

Investigations have shown (1) that check dams may be destroyed if flows scour the gully side slopes below the structures and produce a gap between the dam and the bank. Since water below a check dam is turbulent, eddies develop that flow upstream along each gully side slope. These eddies are the cutting forces.

Several types of material are suitable for bank protection. Loose rock is effective, but should be reinforced with wire-mesh fence, secured to steel posts, on all slopes steeper than 1.25 to 1.00. The design should provide for excavation of the side slopes to a depth of about 0.3 m so that the rock can be placed flush with the surrounding side slope surface to increase stability of the protection. Excavation of surface materials also assures that the rock would not be set on vegetation. Banks should be protected for the full length of the apron.

The height of the bank protection depends on the characteristics of channel, flow, and structure. Where gullies have wide bottoms and spillways are designed to shed the water only on the channel floor, the height shall equal total dam height at the structure but can rapidly decrease with distance from the structure. In contrast, where the waterfall from a check dam will strike against the gully banks, the height of the bank protection shall not decrease with distance from dam to prevent the water from splashing against unprotected banks.

In gullies with V-shaped cross sections, the height of the bank protection should be equal to the elevation of the upper edges of the free boards of the dam. In general, the height of the bank protection can decrease with increasing distance from the dam.

4. EQUATIONS FOR VOLUME CALCULATIONS

After the dam locations have been determined in the field, based on spacing requirements and suitability of the site for a dam, gully cross sections at these locations should be surveyed and plotted. If possible, use the computer program developed by Heede and Mufich (7) to design the dams. Otherwise the dams must be designed from the plotted gully cross sections. Structural and gully dimensions can be used in equations developed by the above authors.

4.1 Loose-rock and Wire-bound Dams

The volume equation for the dam proper of loose-rock and wire-bound dams considers either angular or round rock, because the angle of repose varies with rock shape and influence the side slopes of the dam. The generalized equation is

$$V_{LR} = \frac{H_D^2}{\tan A_R} + 0.6\ HL_A - V_{SP} \qquad (20)$$

where V_{LR} is the volume of the dam proper, H_D represents dam height, 0.6 is a constant that refers to the breadth of dam, L_A is the average length of the dam, tan A_R is the tangent of the angle of repose of the rock type, and V_{SP} is the volume of the spillway. It is assumed that the angle of repose for angular rock is represented by a slope of 1.25:1.00, corresponding to a tangent of 0.8002; for round rock, the slope is 1.50:1.00 with a tangent of 0.6590. L_A is given by the equation

$$L_A = L_B + \frac{L_U - L_B}{2D} H_D \qquad (21)$$

along the thalweg is

$$M_{LB} = 3.50\ H_D \tag{26}$$

where M_{LB} is the length of the wire mesh for the bank protection, and 3.50 is a constant. The width of the wire mesh, measured from the apron to the top of the bank protection at the dam, equals total dam height.

The number of fenceposts is calculated by the equation

$$N_B = 3H_D + 2 \tag{27}$$

where N_B is the number of fenceposts for the bank protection, rounded up to a whole even number, and 2 and 3 are constants, the latter derived from a 1.2 m spacing. Of the total number of posts, half should be 0.75 m taller than the dam; the other half are of dam height.

For wire-bound dams, the length of the wire mesh is taken as that of the dam crest, which includes a safety margin and is calculated by the equation

$$M_L = L_B \quad \frac{L_U - L_B}{D} \quad H_D \tag{28}$$

where M_L is the length of the wire mesh. The width of the mesh, measured parallel to the thalweg, depends not only on dam height but also on rock shape. The equation for the width of the wire mesh is

$$M_W = \frac{2H_D}{\tan A_R} + \frac{2H_D}{\sin A_R} + 3 \tag{29}$$

where M_W is the width and A_R the angle of repose of the rock. For angular rock, this angle is assumed to be $38^\circ 40'$, corresponding to a dam side slope of 1.25:1.00, and for round rock $33^\circ 25'$, representing a slope of 1.50:1.00. The term 3 is a constant, in metre units. Equation (29) provides for an overlapping of the mesh by 1.8 m.

4.2 Single-fence Dams

A zero gully gradient was assumed for calculating rock volume for the dam proper of single-fence dams. This results in overestimates that compensate for simplification of the equation for volume calculation. If the construction plan calls for a dam with a 0.6 m breadth, for ease of calculation, the cross section of the dam parallel to the thalweg is taken as a right triangle with a dam side slope of 1.25:1.00 in the equation

$$V_{SF} = \frac{H_D^{\ 2}}{2(0.80020)} L_A - V_{SSF} \tag{30}$$

where V_{SF} is the rock volume of the dam proper, 2 is a constant, and 0.80020 represents the tangent of a slope of 1.25:1.00. V_{SSF} is the volume of the spillway, calculated by the equation

$$V_{SSF} = H_S \times L_{AS} \times B_{SF} \tag{31}$$

where B_{SF} is the breadth of the dam, measured at half the depth of the spillway and given by the formula

$$B_{SF} = \frac{H_S}{2(0.80020)} \tag{32}$$

The length of wire mesh for a single-fence dam is given by equation (28), while the width equals dam height. The number of fenceposts is calculated by the equation

$$N_{SF} = \frac{L_B}{1.2} \quad \frac{L_U - L_B}{1.2D} \quad H_D + 1 \tag{33}$$

where N_{SF} is the number of posts of the dam proper of a single-fence dam, rounded up to a whole number; 1.2 signifies a distance of 1.2 m between the posts; and 1 is a constant. Of the total number of posts, half are 0.75 m taller than the dam; the other half are dam height.

4.3 Double-fence Dams

The equation for rock volume of a double-fence dam with vertical fences, 0.6 m apart, is:

$$V_{DF} = 0.6H_DL_A - V_{SDF} \tag{34}$$

where V_{DF} is the volume, 0.6 is a constant, and V_{SDF} is the volume of the spillway, computed by the formula

$$V_{SDF} = H_S \times L_{AS} \times 0.6 \tag{35}$$

where 0.6 represents the standard breadth of the dam, in metres.

The length of wire mesh is given by

$$M_{LD} = 2L_B + \frac{L_U - L_B}{D} 2H_D \tag{36}$$

where M_{LD} is the length of the mesh. The width of the wire mesh equals dam height. The number of fenceposts is computed by the equation

$$N_{DF} = \frac{L_B}{1.2} + \frac{L_U - L_B}{1.2D} H_D + 2 \tag{37}$$

where N_{DF} is the number of posts of the dam proper of a double-fence dam, rounded up to a whole even number, and 1.2 is a constant representing a post spacing of 1.2 m. Half of the posts are dam height, while the other half are 0.75 m taller than the dam.

4.4 Head Cut Control

The volume requirements for a head cut control structure are given by the equation

$$V_{HC} = \left(\frac{D^2}{2(0.33333)}\right) \left(\frac{L_U + 3L_B}{4}\right) \tag{38}$$

where V_{HC} is the rock volume, D is the depth of gully at the head cut, 0.33333 is the tangent of the angle that refers to a structure with a slope gradient of 3:1, 2, 3 and 4 are constants. If a slope gradient different from 3:1 is selected, the value of the tangent in the equation should be changed to correspond to that gradient.

4.5 Rock Volume Relations among Dam Types

In the Colorado project, rock volumes required for the various types of check dams were expressed graphically (Figure 11). If this graph is used for decision-making, it must be recognized that double-fence dams had parallel faces 0.6 apart. Where double-fence structures with bases wider than the breadth of dam are required, rock volume requirements will be larger. The graph shows that a loose-rock or wire-bound dam with effective height of 2 m requires 5.5 times more rock than a double-fence dam.

5. CONSTRUCTION PROCEDURES

Before construction starts, the following design features should be staked and flagged conspicuously:

1. Mark the centreline of the dam and the key trenches, respectively, on each bank. Set the stakes away from the gully edge to protect them during construction.

2. Designate the crest of the spillway by a temporary bench-mark in the gully side slope sufficiently close to be of value for the installation of the dam.

3. Mark the downstream end of the apron.

4. For loose-rock and wire-bound dams, flag the upstream and downstream toes of the dam proper.

Caution is required during excavation to avoid destroying the stakes before the main work of installation begins.

The construction of all dams should start with the excavation for the structural key (Figure 12), the apron, and the bank protection. This very important work can be performed by a backhoe or hand labour. Vegetation and loose material should be cleaned from the site at the same time.

Generally, the trenches for the structural keys will have a width of 0.6 m, therefore an 0.5 m wide bucket can be used on the backhoe. If the construction plan calls for motorized equipment, two types of backhoes can be used. One, mounted on a rubber-wheeled vehicle and operating from a turntable, permits the backhoe to rotate 360°. This machine travels rapidly between locations where the ground surfaces are not rough, and works very efficiently in gullies whose side slopes and bottoms can be excavated from one or both channel banks. The other type can be attached to a crawler tractor. This type proves to be advantageous at gullies that are difficult to reach, and with widths and depths so large that the backhoe has to descend into the channel to excavate. In deep gullies with V-shaped cross sections, temporary benches on the side slopes may be necessary. Often, the bench can be constructed by a tractor with blade before the backhoe arrives.

The excavation material should be placed upstream from the dam site in the gully. The excavated trench and apron should then be filled with rock. Since a special graded rock is required for the keys, rock piles for keys must be separate from those used in the apron and dam proper. Excavations can be filled by dumping from a dump truck or by hand labour. During dumping operations, the fill must be checked for voids, which should be eliminated.

If dump trucks are loaded by a bucket loader, some soil may be scooped up along with the rock. Soil is undesirable in a rock structure because of the danger of washouts. To avoid soil

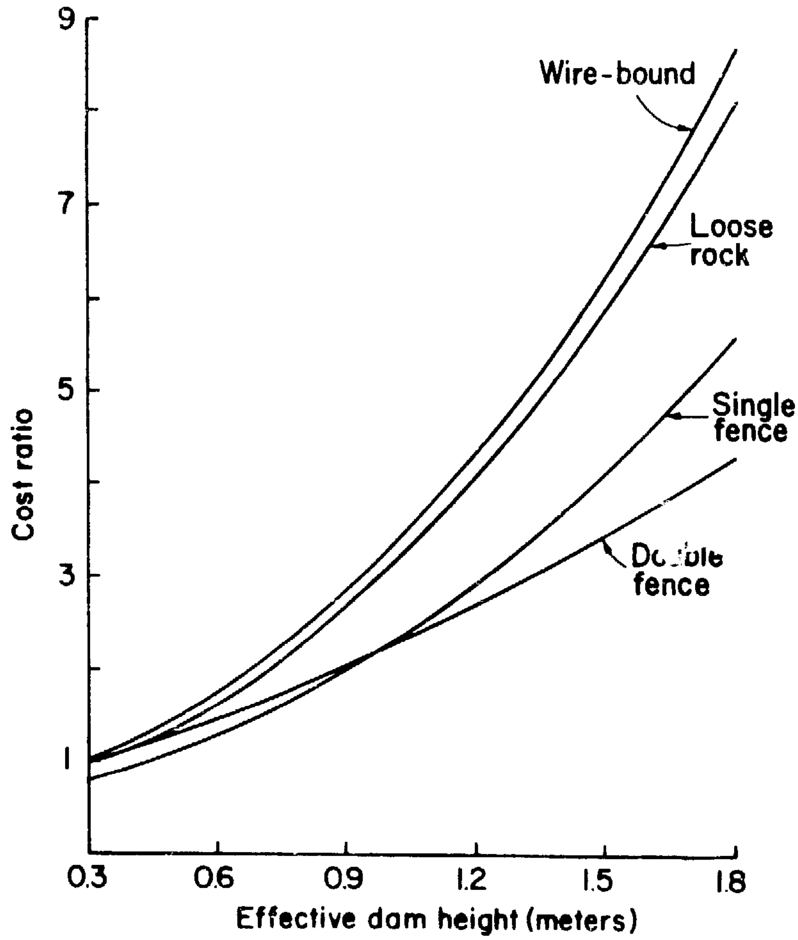

Figure 15. Installation cost of four different types of check dams as a function of effective dam height. The cost ratio is the cost of a dam related to the cost of a 0.3 m high loose-rock dam built with angular rock.

additions, a bucket with a grilled bottom can be used that can be shaken before the truck is loaded. Other devices such as a grilled loading chute would also be applicable.

Dumping rock into the dam proper has two advantages: the structure will attain greater density and rocks will be closer to their angle of repose than if placed by hand. Hand labour can never be completely avoided, however, since larger voids and the final dam shape require hand placement. Where gullies are deep and dumping is impractical, rock chutes may be used. Certainly, more sophisticated equipment such as a clamshell can facilitate the filling operations, especially at double-fence dams. Often, however, gully control projects are planned to employ people in larger numbers. This objective can easily be accomplished if sufficient supervision is available for the individual steps in the construction. Special attention is needed at the spillway and free board. In loose-rock and wire-bound structures, where the shape of the dam is not outlined by a fence as in the other types, experience shows there is a tendency to construct the spillways smaller than designed.

In wire-bound dams, a commercial, galvanized stock fence, usually about 1.2 m wide can be used. The stay and line wires should not be less than $12\frac{1}{2}$ gauge low-carbon steel, the top and bottom wires 10 gauge low-carbon steel, and the openings in the mesh 0.15 m. To connect ends of the fence or to attach the fence to steel posts, a galvanized $12\frac{1}{2}$ gauge coil wire is sufficiently strong.

The wire mesh of required length and width should be placed over the gully bottom and side slopes after the trench and apron have been filled with rock (Figure 13). Generally, several widths of mesh will be needed to cover the surface from bank to bank. If several widths of fence material are required, they should be wired together with coil wire where they will be covered with rocks. The parts not to be covered should be left unattached to facilitate the fence-stringing operations around the structure.

Before the rock is placed on the wire mesh for the installation of the dam proper, the mesh should be temporarily attached to the gully banks. Otherwise, the wire mesh lying on the gully side slopes will be pushed into the gully bottom by the falling rock and buried. Usually, stakes are used to hold the wire mesh on the banks.

After the dam proper is placed and shaped, the fence can be bound around the structure. Fence stretchers should be applied to pull the upstream ends of the fence material down tightly over the downstream ends, where they will be fastened together with coil wire. Then the bank protection below the dam should be installed.

The installation of single- and double-fence dams begins with the construction of the fences after excavation is completed (Figure 14). Construction drawings should be followed closely here, because the final shape of the dams will be determined by the fences. Conventional steel fence posts can be used. In some locations, the great height of posts may offer difficulties for the operator of the driving equipment, and scaffolds should be improvised.

At single-fence dams, dumping of rock is practical if the gully is not excessively deep or wide. At double-fence structures, hand labour, or a backhoe or clamshell, will be required. The rock should be placed in layers and each layer inspected for large voids, which should be closed manually by rearranging rocks.

Much time and effort can be saved during construction if a realistic equipment plan is established beforehand. Such a plan requires an intimate knowledge of the cross-sectional dimensions of the gullies and their accessibility to motorized equipment. The amount of pioneer roads that will be needed because of lack of access is not only important for equipment considerations, but will also enter into the cost of the construction.

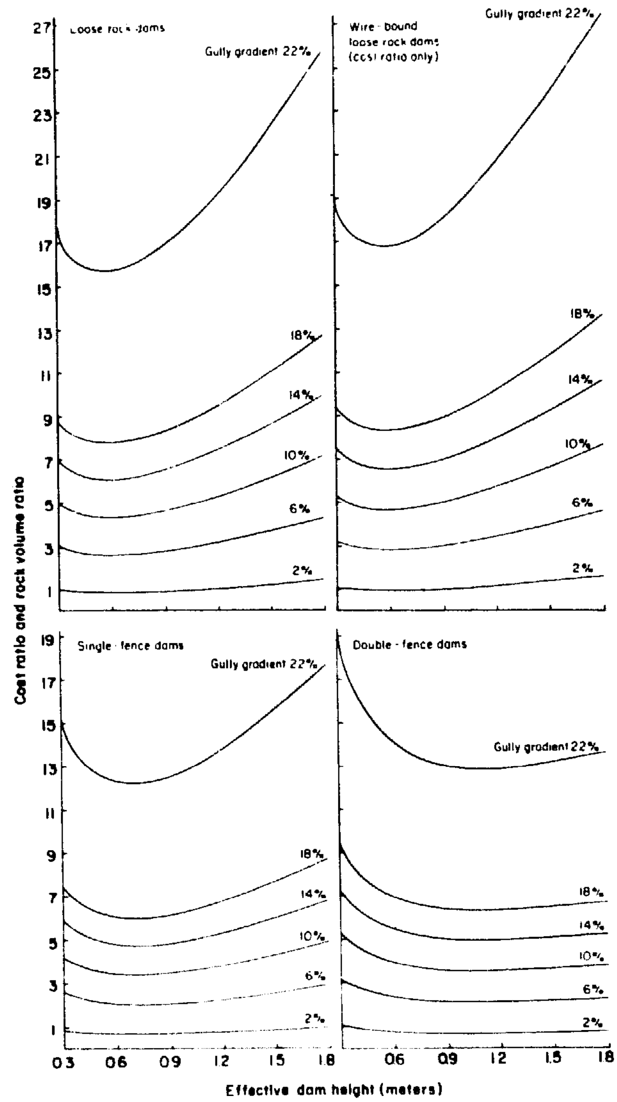

Figure 16. Relative cost of installation of check-dam treatments and relative angular rock volume requirements in gullies with different gradients as a function of effective dam height. The cost ratio relates the cost of a treatment to that of a treatment with loose-rock dams 0.3 m high installed on a 2% gradient. The rock volume ratio relates the volume required by a treatment to that of a treatment with 0.3 m loose-rock dams installed on a 2% gradient.

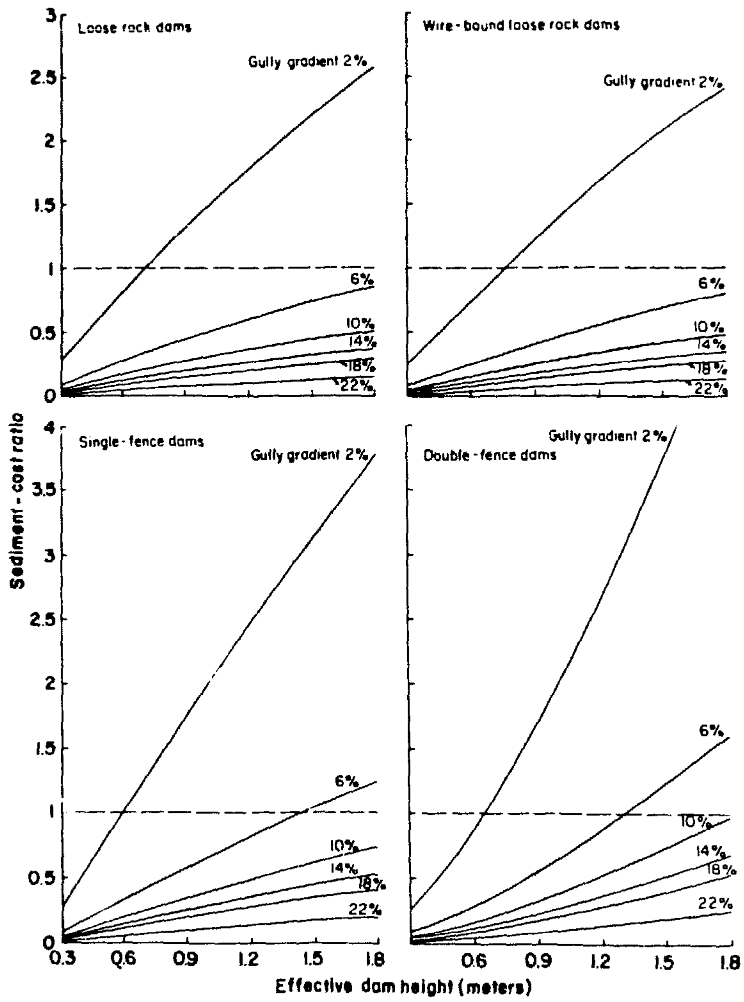

Figure 17. The sediment-cost ratio relates the value of the expected sediment deposits to the cost of treatment. The graphs show this ratio as a function of effective dam height on gully gradients ranging from 2 to 22%. The base cost was taken as \$ 20/m^3 of angular rock dam and the value of 1 m^3 of sediment deposits assumed at one-tenth of that cost.

If equipment is to be used, as a general rule (in the Colorado context at least), it appears to be advantageous to use heavier and larger machines if their mobility is adequate. Although hourly costs for heavier machines are usually greater, the total cost for a job is reduced.[1/]

With few exceptions, conventional construction equipment is not sufficiently mobile to operate in rough topography without pioneer roads. In watershed rehabilitation projects such as gully control, roads are undesirable because any road construction disturbs the ground surface and may lead to new erosion. It is therefore desirable to consider crawler-type equipment only.

Limited mobility of the machinery may result from one or all of the following factors: (1) insufficient engine power, (2) large total weight of the machinery, or (3) mounting of the equipment on rubber wheels. A good example is the backhoe. If a crawler-type backhoe with a powerful engine is used, the equipment may be so heavy that it cannot climb slopes steeper than 20 percent. If a lighter crawler-type backhoe is used, the engine may lack the power for unlimited operations in rough topography, and pioneer roads will be needed.

6. COST RELATIONS

Relationships between the installation costs of the four different types of rock check dams described here are based on research in Colorado. The relationships are expressed by ratios (Figure 15) to avoid specific monetary unit comparisons. When considering the cost ratio, one must keep in mind that differential inflation may have offset some finer differences in cost. It is advisable, therefore, to test the cost of individual structures by using material and volume requirements as given by the equations. The cost ratios in Figure 15 can then be adjusted, if necessary.

In a given gully, for example, a double-fence dam with an effective height of 1.8 m costs only about four times as much as a 0.3 m loose-rock dam, while a wire-bound dam 1.8 m high costs 8.5 times as much as a 0.3 m loose-rock dam. Costs will change with different sizes and gradients of gullies, but the general relationships will not change.

It is obvious that the cost of installing a complete gully treatment increases with gully gradient because the required number of dams increases. Figure 16 indicates there is one effective dam height at which the cost is lowest. In the sample gully, this optimum height for loose-rock dams is about 0.6 m, for single-fence dams 0.7 m, and for double-fence dams 1.1 m. A constant gully cross section was assumed. In reality, of course, gully cross sections change between dam sites usually. The optimum height for lowest treatment costs is not a constant, but changes between gullies, depending on shape and magnitude of the gully cross sections at the dam sites.

Since the cost of the dam is directly proportionate to the rock volume, Figure 16 also expresses the relationship between rock requirement and effective dam height. This means that, in a given gully, there is one dam height at which rock requirements for a treatment are smallest.

1/ Editor's note: There are obviously a number of countries where labour-intensive projects are desirable or where machines are either not available or too expensive (compared to a labour-intensive approach). The author's findings vis-à-vis economics of machines must of course be judged in terms of the readers' particular needs and objectives.

A treatment cannot be evaluated on the basis of cost of installation alone, because recognition of benefits is part of the decision-making process. Sediment deposits ratained by check dams can be incorporated into a cost ratio that brings one tangible benefit into perspective. The sediment-cost ratio increases (treatment is increasingly beneficial) with dam height and decreases with increasing gradient (Figure 17). The example in Figure 17 shows that a treatment consisting of loose-rock dams on a 2 percent gradient has a sediment-cost ratio larger than 1.0 for effective dam heights of 0.75 m and above. The large ratio is explained by the fact that a gully with a 2 percent gradient requires only a small number of dams (Figure 9), while volumes of sediment deposits do not decrease significantly with number of dams or with gradient.

Since single-fence and double-fence dams cost less than loose-rock and wire-bound loose-rock dams for an effective height greater than 0.3 m, the sediment-cost ratio is more favourable for the fence-type structures. The ratios remain smaller than 1.0 on all gradients larger than 5 percent for treatments with loose-rock and wire-bound loose-rock dams, and on gradients larger than 7 and 9 percent for treatments with single-fence and double-fence dams, respectively.

The importance of sediment-cost ratios in relation to gully gradient and effective dam height becomes apparent in situations where not all gullies of a watershed can be treated. Gullies with the smallest gradient and largest depth, and highest possible fence-type dams should be chosen if other aspects such as access or esthetic value are not dominant.

7. OTHER GULLY CONTROL STRUCTURES AND SYSTEMS

7.1 Non-porous Check Dams

Rock can be used for the construction of wet masonry dams. Limitations in available masonry skills, however, may not permit this approach. A prefabricated concrete dam was designed and a prototype installed in Colorado (2) that required very little time and no special skills for installation. The capital investment for this dam is larger than for a rock structure, however. A prestressed concrete manufacturer must be available reasonably close to the project area, and the construction sites must be accessible to motorized equipment. Where esthetic considerations and land values are high - recreational sites and parks, for example - a prestressed, prefabricated concrete check dam may be the answer.

Check dams built from corrugated steel sheet may also be used. For successful application, a pile driver is required to assure proper fit of the sheets. Excavating trenches for the sheets jeopardizes dam stability if the refill is not compacted sufficiently. Quite often, insufficient depth of soil above the bedrock does not permit this dam type.

7.2 Earth Check Dams

Earth check dams should be used in gully control only in exceptional cases. Basically, it was the failure of the construction material, soil, that in combination with concentrated surface runoff, caused the gully. Gullies with very little flow may be an exception if the emergency spillway safely releases the flow on to the land outside of the gully. The released flow should not concentrate, but should spread out on an area stabilized by an effective vegetation cover or by some other type of protection such as a gravel field. Most gullied watersheds do not support areas for safe water discharge.

Stand-pipes or culverts in earth check dams generally create problems, because of the danger of clogging the pipe or culvert inlet, and the difficulty in estimating the possible largest storm for the design period. Therefore, additional spillways are required.

If soil is the only dam material available, additional watershed restoration measures such as vegetation cover improvement work and contour trenches should be installed to improve soil infiltration rates, to enhance water retention and storage, and thus decrease magnitude and peak of gully flows.

7.3 Vegetation-lined Waterways

With the exception of earth check dams, gully control measures described previously treat the flow where it is - in the gully. In contrast, treatments by waterways take the water out of the gully by changing the topography. Check dams and waterways both modify the regimen of the flow by decreasing the erosive forces of the flow to a level that permits vegetation to grow. In waterways, however, flow is modified compared with the original gully, in two ways (Heede 1968): (i) lengthening the watercourse results in a gentler bed gradient; and (ii) widening the cross section of flow provides very gentle channel side slopes. This latter measure leads to shallow flows with a large wetted perimeter (increase in roughness parameter). Both measures substantially decrease flow velocities, which in turn decrease the erosive forces.

Contrasted with check dam control, waterway projects strive to establish a vegetation cover when land reshaping is finished. Indeed, a quick establishment of an effective vegetation lining is the key to successful waterways. It follows that the prime requisites for a successful application are precipitation, temperature, and fertility of soils, all favourable to plant growth. Other requisites are:

1) Size of gully should not be larger than the available fill volumes;

2) Width of valley bottom must be sufficient for the placement of a waterway with greater length than that of the gully;

3) Depth of soil mantle adequate to permit shaping of the topography; and

4) Depth of topsoil sufficient to permit later spreading on all disturbed areas.

Vegetation-lined waterways require exact designs, close construction supervision, and frequent inspections during the first treatment years. The risk, inherent to nearly all types of erosion control work, is greater for waterways at the beginning of treatment than for check dam systems. To offset this risk, in Colorado, 19 percent of the original cost of installation was expanded for maintenance, while for the same period of time only 4 percent was required at check dams (5).

Eight percent less funds were expended per linear metre of gully for construction and maintenance of grassed waterways than for check dams. This cost difference is not significant, especially not if the greater involvement in waterway maintenance is recognized. In deciding on the type of gully control, one should consider not only construction costs but also risk of and prerequisites for vegetation-lined waterways.

8. SUMMARY OF DESIGN CRITERIA AND RECOMMENDATIONS

Spacing decreases with increasing gully gradient and increases with effective dam height (Figure 8). Number of check dams increases with gully gradient and decreases with increasing effective dam height (Figure 9). Expected volumes of sediment deposits increase with effective height (Figure 10).

For practical purposes, gully gradients ranging from 1 to 30 percent do not influence volumes of sediment deposits in a treatment. On gradients larger than 30 percent, sediment catch decreases more distinctly with increasing gradient.

Rock volume requirements are much larger for loose-rock and wire-bound loose-rock dams than for fence-type dams. At effective dam heights larger than 0.6 m, treatments with double-fence dams require smallest amounts of rock (Figure 11).

At effective dam heights larger than about 0.5 m, loose-rock and wire-bound loose-rock dams are more expensive than fence-type dams. The difference in cost increases with height (Figure 15). Single-fence dams are less expensive than double-fence dams at effective heights up to 1.0 metre.

Regardless of gradient, in a given gully, there is one effective dam height for each type of structure at which the cost of treatment is lowest (Figure 16). For each type of treatment, rock requirements are smallest at the optimum effective dam heights for least costs (Figure 16). The sediment-cost ratio (the value of expected sediment deposits divided by the cost of treatment) increases with effective dam height and decreases with increasing gully gradient (Figure 17). At effective dam heights of about 0.6 m and larger, single-fence dams have a more pronounced beneficial sediment-cost ratio than loose-rock or wire-bound loose-rock dams. At effective dam heights of 1.1 m and larger, treatments with double-fence dams have the largest sediment-cost ratios (Figure 17).

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10. SYMBOLS USED IN THIS PAPER

a = the angle corresponding to the gully gradient.

A_R = the angle of repose of rock.

B_A = the breadth of loose rock or wire-bound loose-rock dams, measured at one-half of the depth of spillway.

B_{SF} = the breadth of single-fence dams, measured at one-half of the depth of spillway.

C = the discharge coefficient, taken as 1.65.

c = a constant whose value changes with groups of gully gradients.

D = the depth of gully.

D_{65} = the sieve size in the rock of which 65 percent are finer.

d = a constant whose value changes with groups of gully gradients.

f = a constant whose value changes with groups of gully gradients.

G = the gully gradient in percent.

g = the acceleration due to gravity, taken as 9.81 m/s^2.

H = the head of flow above weir crest.

H_D = the total height of dam.

H_E = the effective height of dam, the elevation of the crest of the spillway above the original gully bottom.

H_S = the depth of spillway of a dam installed in a rectangular or trapezoidal gully.

H_{SV} = the depth of spillway for a dam installed in a V-shaped gully.

K = a constant, referring to the expected sediment gradient.

L = the effective length of the weir.

L_A = the average length of dam.

L_{AS} = the effective length of spillway.

L_B = the bottom length of the gully.

L_{BS} = the bottom length of the spillway of a dam installed in a rectangular or trapezoidal gully.

L_{BSV} = the bottom length of the spillway of a dam installed in a V-shaped gully.

L_{HE} = the average length of dam.

L_U = the width of the gully between the gully brinks.

L_{US} = the length between the brinks of the spillway of a dam installed in a rectangular or trapezoidal gully.

L_{USV} = the length between the brinks of the spillway of a dam installed in a V-shaped gully.

M_L = the length of the wire mesh of a wire-bound dam.

M_{LB} = the length of the wire mesh of the bank protection, measured parallel to the thalweg.

M_{LD} = the length of the wire mesh for a double-fence dam.

M_W = the width of the wire mesh of a wire-bound dam, measured parallel to the thalweg.

N_B = the number of fenceposts of the bank protection work.

N_{DF} = the number of fenceposts of the dam proper of a double-fence dam.

N_{SF} = the number of fenceposts of the dam proper of a single-fence dam.

Q = the rate of the peak flow in m^3/s, based on the design storm.

q = the rate of the peak flow in m^3/s per unit width of spillway.

R = a constant, representing the depth of key.

S = the spacing of check dams.

V_A = the volume of the apron and bank protection.

V_c = the critical velocity at dam crest.

V_{HC} = the volume of a head cut control structure.

V_{DF} = the volume of the dam proper of a double-fence dam.

V_K = the volume of the key.

V_{LR} = the volume of the dam proper of a loose-rock dam.

V_O = the approach velocity of flow.

V_S = the volume of sediment deposits above check dams.

V_{SF} = the volume of the dam proper of a single-fence dam.

V_{SP} = the volume of the spillway of loose rock and wire-bound loose-rock dams.

V_{SDF} = the volume of the spillway of a double-fence dam.

V_{SSF} = the volume of the spillway of a single-fence dam.

W = the weight of rock related to D_{65}.

x = the horizontal coordinate of a point on the trajectory, here the horizontal distance between the downstream side of the spillway and the point where the waterfall hits the apron.

Y_c = the critical depth of flow at dam crest.

z = the vertical coordinate of a point on the trajectory, here the effective dam height.

XIII.

LOGGING AND THE ENVIRONMENT, WITH PARTICULAR REFERENCE TO SOIL AND STREAM PROTECTION IN TROPICAL RAINFOREST SITUATIONS

by

D.A. Gilmour[1]

1. INTRODUCTION

Forests provide a number of resources of benefit to mankind of which timber is only one (admittedly the most important one in many forested areas). The other main resources which forests provide are water, forage, wildlife and recreation. In certain situations one or more of these other resources may be of more importance than timber, and forest management practices must take account of this. Management of forest land to utilise these five basic resources is termed multiple use management.

When there is an abundance of natural resources and few people, there is little need for multiple use management; but when an increasing number of people have to rely on an unchanging or diminishing resource level, they must make the most effective use of the resources available.

In applying a system of multiple use management there are bound to be conflicts between uses, e.g. between the use of a catchment for water and for timber. Under multiple use management it is seldom possible to get optimum production of any one resource because of the concessions that have to be made to accommodate the others. However, properly applied it will yield the greatest total benefits to the public from the use of all the resources.

Harvesting of timber causes a number of changes in the environment, and in recent years logging and silvicultural practices have been criticised on these grounds alone, i.e. that they have caused a change in the natural environment. Consequently it is important from a number of points of view that forest operations cause the minimum impact on the environment.

This paper deals with methods of protecting soils and streams during and after logging operations - the effectiveness of some of the methods - and some of the problems encountered in instituting changes in current logging techniques. Examples are given from a rainforest area of North Queensland (humid tropical climate of 2 700 mm rainfall average).

1/ Forestry Office, Atherton, Queensland, Australia.

Figure 1 - Deep erosion gully in granite soil under rainforest formed when a snig track removed the stable surface soil and no provision was made for drainage. The man is the centre of the photo gives an idea of the scale.

2. DAMAGE CAUSED BY LOGGING

Logging can cause a number of changes to the environment, and the major ones are listed below:

(a) Erosion and subsequent siltation of streams and reservoirs.

(b) Changing the streamflow regime (quantity, quality and timing) and increasing stream water temperatures.

(c) Altering the environment for animals and birds, e.g. by changing the species composition of the forest and by removing harborage and nesting sites.

As indicated in the Introduction, this paper will concentrate on the methods of keeping erosion and siltation to a minimum.

Tree felling (as such) causes virtually no soil disturbance. The problems start once the fallen trees are moved. In other words it is the roads and snig tracks (log skid trail) which are the potential originators of excessive surface runoff and erosion.

The amount of erosion that occurs after logging is dependent (to some extent) on the amount of bare soil produced, and this varies with the logging system. Rice and his co-workers (1) found that the area of bare soil after logging in northwestern U.S.A. ranged from 1-2% for a helicopter clearcut to 25-30% for a jammer group selection cut. Studies in North Queensland, Australia, have shown that after group selection tractor logging in rainforest, between 18 and 21% of areas are covered by snig tracks. (Data on file, Queensland Forestry Department, Atherton). About 70% of this area would be bare soil.

However, it must be remembered that many species require bare soil to regenerate; therefore, some conscious denuding of the surface soil may be a desirable regeneration practice.

Erosion is possible once the soil is exposed to the pounding effect of raindrops and the erosive force of running water. Undisturbed surface soil in a forest is normally well structured, cohesive, and resistant to erosion due to the properties imparted by the vegetation. Organic matter in the form of leaves, bark, etc. is being continually incorporated into the soil by the micro-organisms to provide this well structured surface soil.

Subsoil, on the other hand, is frequently quite dispersive, i.e. it breaks into its ultimate particles of sand, silt and clay very easily when it becomes wet. This is illustrated in Table 1 which presents dispersion ratio data for various depths in a granite soil on the Atherton Tableland in far north Queensland, Australia.

Table 1

Dispersion ratios[1/] for various depths in a granite soil under rainforest at Danbulla on the Atherton Tableland of far north Queensland, Australia.

Depth (cm)	Dispersion Ratio (%)
0-15	0.6
15-30	16.0
60	57.0
500	77.0

[1/] The Dispersion Ratio was first proposed by Middleton (2) in 1930 as an index of soil erodibility and has since been used by many investigators (3,4). It measures the degree of water stable aggregation of the silt plus clay fraction of the soil. Middleton recommended that soils with a Dispersion Ratio greater than 10 be regarded as erodible while those with a Dispersion Ratio of less than 10 be regarded as non-erodible.

It is evident that the soil illustrated in Table 1 has a very stable surface, but that once this stable surface has been removed (e.g., by the construction of a snig track) the subsoil is extremely prone to erosion. In fact this particular soil type gave rise to massive erosion after logging when insufficient attention was paid to drainage of the snig tracks, as illustrated in the deep gully of Figure 1.

The erosion products carried by the surface runoff eventually find their way into streams unless these materials are diverted. Once in the streams the fine particles are frequently carried in suspension while the coarse particles increase the bed load component. Muddied streams cause problems if the water is used by industry or for domestic supplies. In addition, fish habitat frequently suffers from excess sedimentation (5,6).

3. GUIDELINES FOR MINIMISING EROSION AND STREAM SEDIMENTATION

3.1 General Guidelines

Once a forest is disturbed by logging some erosion is bound to occur. It is quite impossible to eliminate erosion completely - all that can be done is to keep it to a minimum. A good deal of information is available outlining various prescriptions and techniques for reducing soil erosion and stream sedimentation from logged areas (e.g. 7,8, 9,10,11,12,13). All that is intended here is to give some general guidelines which are applicable to any area. These are listed below:

(a) Stream buffer strips: Keep all roads, snig tracks and log ramps as far away from stream courses as possible.

(b) Snigging: Where tractor logging is used, "dead snigging" should be avoided, instead making use of a logging arch.

(c) Grades: Keep grades on all roads and tracks as low as possible.

(d) Drainage: Ensure adequate drainage of all roads and tracks.

(e) Uphill vs downhill: Practice uphill logging wherever practicable.

(f) Putting to bed: At the completion of each logging season put roads and tracks "to bed", and apply special treatment to any problem areas (seeding with grass etc.) Each of these will now be discussed in turn.

3.2 Stream Buffer Strips

Protective strips along streams will ensure that any surface runoff and erosion which does occur will have some opportunity of being diverted into undisturbed areas to be filtered before reaching the stream. When roads have to cross streams, log bridges or concrete culverts should be built. Figure 2 shows a poorly constructed earth and log fill crossing in north Queensland. Such crossings wash out each wet season causing considerable downstream sedimentation. Various studies have shown that a few small sediment source areas can be major contributors in the erosion and sedimentation of catchments (14, 15) and the crossing shown in Figure 2 is an obvious example.

In certain critical areas such as domestic water supply catchments and around reservoirs, all logging activities should be excluded from an area along each bank of the stream and within a certain distance of the normal high water level of the reservoir. The width of this untouched buffer strip will vary depending on the local conditions of soil, topography, vegetation, rainfall regime, etc. However, it is generally recommended that the width should be at least 20 metres on each side of the stream.

Figure 2 – Earth and log fill crossings such as the one depicted here are potent sources of downstream sedimentation when they become washed out during the wet season.

Vegetation maintained along streambanks also prevents water temperatures from rising. Figure 3 shows the impact on maximum water temperatures of removing rainforest vegetation from a small catchment in north Queensland. Mean maximum monthly temperatures were increased by about 1°C in winter and 2°C in summer, although minimum temperatures were unaltered by the clearing.

3.3 Snigging (Skidding) Effects

Dead snigging, i.e. the snigging of logs along the ground behind a tractor, causes unnecessary soil disturbance and gouging of snig tracks - frequently turning them into well defined water ways which are difficult to drain. Figure 4 illustrates the sort of damage which results from dead snigging. The use of some form of logging arch to lift the end of the logs clear of the ground will assist in reducing this sort of damage.

3.4 Road and Snig Track Layout and Design

It is important that road and snig track grades be kept as low as possible, because the erosion potential of surface runoff increases with velocity. Ensuring drainage of roads and snig tracks is a self evident method of reducing erosion and stream sedimentation. It is important to divert surface runoff from roads and tracks before it has a chance to build up sufficient velocity to be a serious erosion force. Drainage water diverted into undisturbed forest has a chance of filtering out its sediment load before reaching the steam. More detailed guides for spacing of drains on roads and tracks are given in Megahan's paper in this publication and in a number of other sources, e.g. 9 and 13. However, in most cases an assessment of each area will be necessary to take into account local variations of soil type, topography, rainfall regime, etc.

3.5 Uphill Logging Advantage

Figure 5 shows a hypothetical pattern of snig track development under both uphill and downhill logging. It is evident that with downhill logging water has the opportunity of concentrating on the lower slopes along main snig tracks and causing a considerable erosion and sedimentation hazard. Uphill logging on the other hand, concentrates the main snig tracks on the ridges so that surface runoff flows into progressively less disturbed areas as it moves downslope.

3.6 Putting Tracks "To Bed"

At the completion of each logging season the area should be inspected and roads and snig tracks put "to bed". Water bars should be constructed where necessary to ensure adequate drainage during the wet season. Most logging road drainage is carried out for "average" conditions, i.e. very low return period flood events, and this is frequently inadequate to cope with wet season rainfall (particularly in tropical areas which experience a pronounced wet season).

Any critical areas such as large road fills, or roads and tracks close to streams or reservoirs should be inspected and, if necessary, seeded with a rapidly growing grass in order to stabilize them as soon as possible (also note the paper on "hydroseeding" in this publication). Mention was made earlier of the importance of a few sediment source areas contributing more than their share (on an area basis) of surface runoff and erosion, and it is the attention to what appears to be minor details which will markedly improve the overall erosion and sedimentation picture.

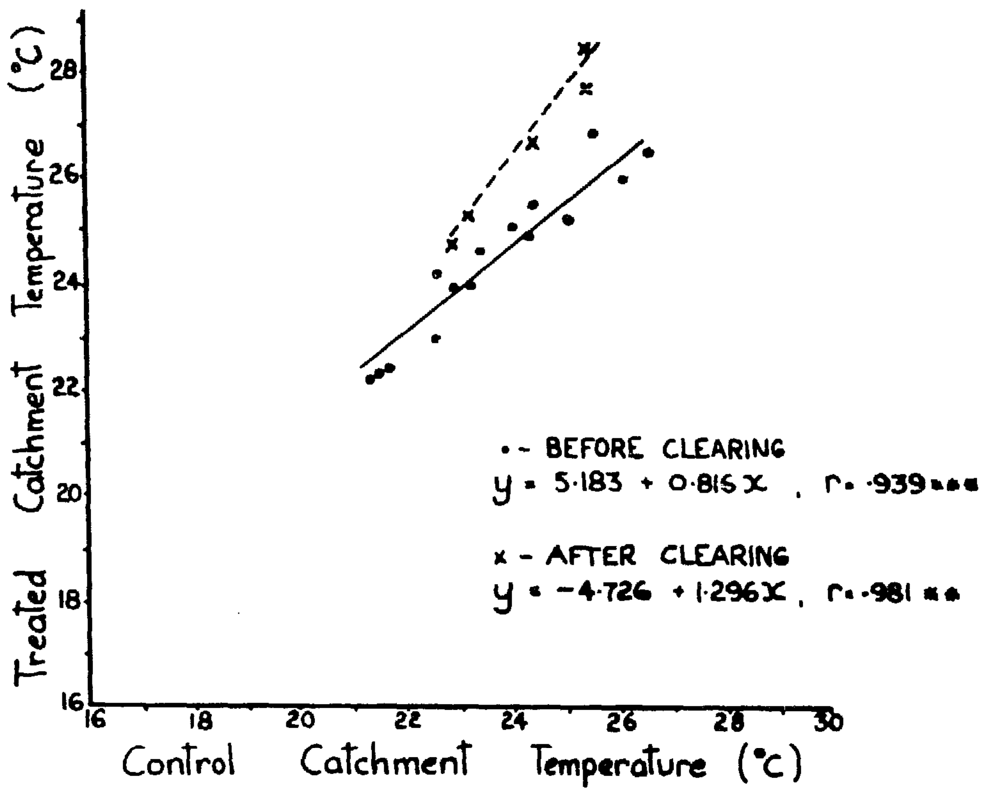

Figure 3 - Effect of vegetation removal on mean maximum monthly stream temperature in a 18 hectare catchment in North Queensland.

Figure 4 - Deep scouring of snig tracks caused by dead snigging logs. The use of a logging arch to lift the end of the logs reduces this form of damage.

4. PUTTING THE GUIDELINES INTO PRACTICE

From a practical point of view individual areas should be assessed when they are first considered for logging, so that conditions can be inserted into timber sale agreements aimed at keeping erosion and stream sedimentation to a minimum. The conditions will be dependent on local environmental factors such as vegetation, geology, soil, topography and rainfall regime. The end use of the water also needs to be taken into account. For example, more stringent conditions will need to be applied in domestic water supply catchments than in areas where the water has no significant downstream use.

This assessment of individual areas is quite essential because of the widely varying conditions even within relatively small areas. For example, a logging practice which is acceptable in one area may be quite unacceptable in another adjacent area because of a change in the soil parent material from a stable sediment to a highly dispersive granite.

The assessment of areas before logging and the determination of special conditions to be applied to those areas means a substantial element of pre-planning for the entire logging operation. The type of logging (uphill or downhill), the location of roads, snig tracks and log ramps, the location and type of stream crossings, the type of machinery to be used - should all be decided before the operation commences. This involves a rather radical change from routine practice in many areas, where "logger's choice" is the rule rather than the exception. However it is a necessary change if we are to keep the environmental impact of logging to a minimum.

In spite of the need to lay down detailed conditions for each sale area, it is desirable to maintain a certain degree of flexibility so that on-the-spot decisions can be made to take account of particular circumstances; e.g. it may be decided that a tree just within a buffer strip can be cut without causing any damage to soil or water values while another tree some distance outside a buffer strip should be left uncut (possibly because it was leaning towards the stream on a steep slope). Such a flexibility throws the onus on to individuals who must take responsibility for their decisions - they can't hide behind the regulations. This means, of course, that field operators must be skilled and well trained.

5. A RAINFOREST EXAMPLE OF THE EFFECTIVENESS OF GUIDELINES IN CONTROLLING EROSION AND SEDIMENTATION

5.1 Description of the Example Area

The guidelines outlined in section 3 above, were used to draw up a set of conditions to be applied to timber sales in a 44 km^2 catchment in north Queensland. These conditions are shown in section 5.3. The vegetation was virgin rainforest which was being logged heavily prior to a portion of it being cleared for the construction of a domestic water supply reservoir for the city of Cairns. The climate is a humid tropical one with an average rainfall of 2 700 mm, about 60% of which falls during the wet season months of January to April.

5.2 The Problems Before Guidelines Were Used

Very little regard was placed on water values when logging commenced in 1960, and by 1965 severe erosion was occurring from roads and snig tracks and serious sedimentation was occurring in the streams. There were many examples in the catchment of snigging and hauling through major streams and there was little attention paid to the location of roads, tracks and log ramps. Some ramps were almost in the streambeds and drainage water was discharged directly into the streams.

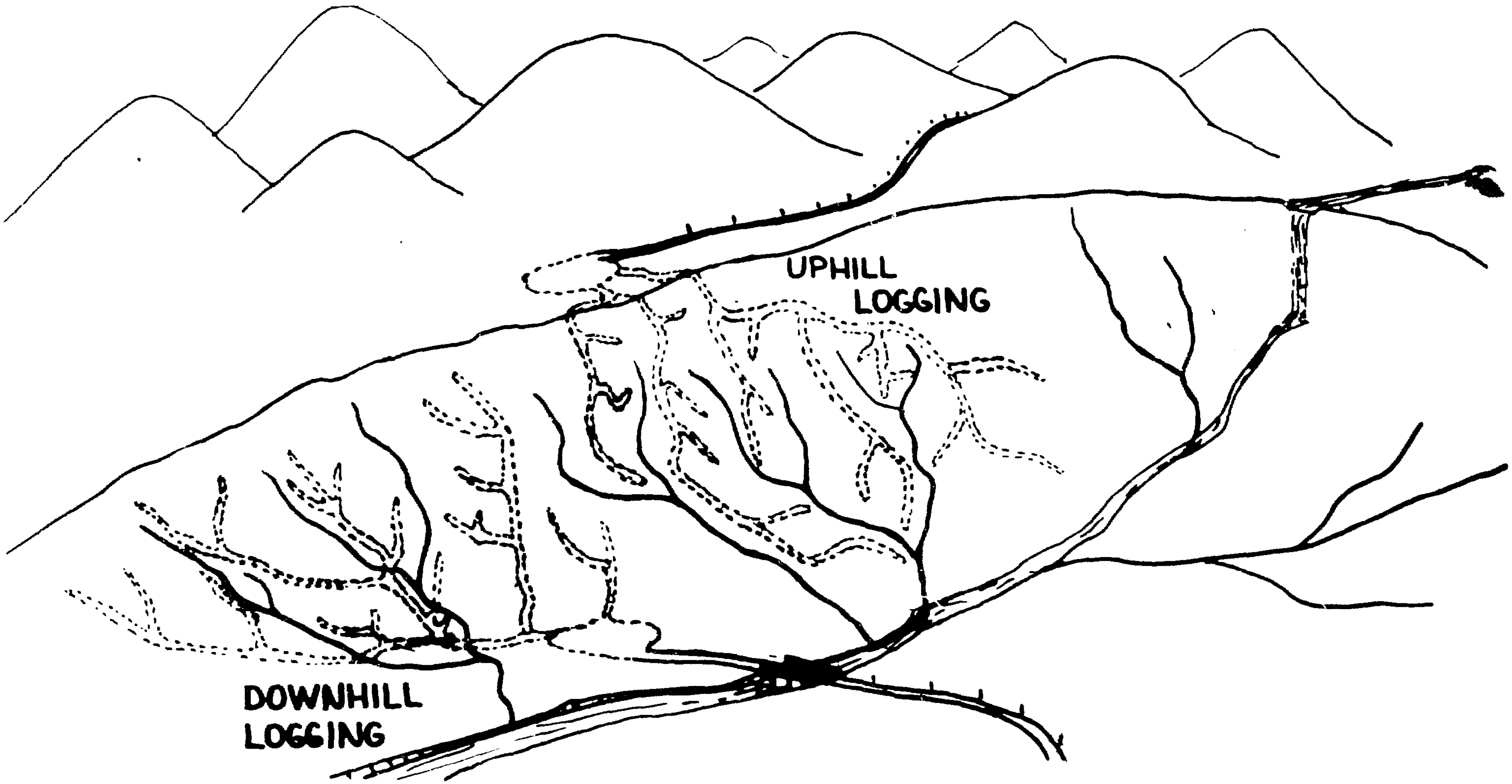

Figure 5 – Hypothetical snigtrack pattern for uphill and downhill logging (dashed lines). With uphill logging water from tracks flows on to progressively less disturbed areas as it moves downslope, reducing erosion hazard. Downhill logging, on the other hand, concentrates surface runoff on the lower slopes along main snig tracks, causing a considerable erosion and sedimentation hazard.

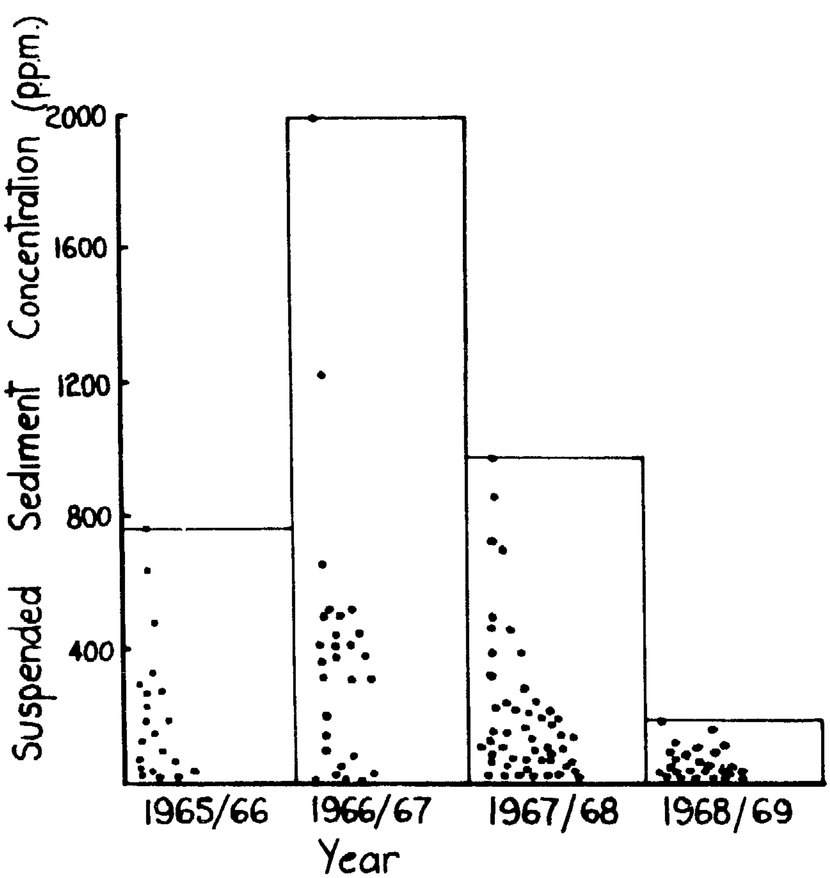

Figure 6 - Suspended sediment concentrations from sampling locations below the area of logging in Freshwater Creek basin in North Queensland from 1965-66 to 1968-69. Conditions to reduce erosion and sediment were introduced in 1967. Each dot represents a single suspended sediment sample.

5.3 Guidelines Established in the Example

In 1967 Special "conditions"(or regulations) were inserted in all the timber sale agreements in the catchment. These conditions were aimed at reducing erosion and stream sedimentation in Freshwater Creek basin in north Queensland. The principal points were:

(1) "The location of all proposed roads, major snig tracks and log ramps shall be subject to approval by the Forest Officer in charge".

(2) "Snigging and hauling through running streams is prohibited".

(3) "The Purchaser shall construct and maintain drains from roads, snig tracks and log ramps as required by the Forest Officer and to his satisfaction".

(4) "Before constructing a crossing of a stream the Purchaser shall secure permission from the Forest Officer and the conditions of such permit shall be observed by the Purchaser. Such conditions may specify the manner in which spoil,if any, is to be disposed of".

(5) "A logging arch or bobtail shall be used for snigging operations when this is required by the Forest Officer".

(6) "The Forest Officer in charge may suspend all or any operations at any,and for such,time as he considers these operations detrimental to water or forest interests".

5.4 Effects of the Guidelines (in the Example)

Measurements of suspended sediment concentration were made from 1965 until 1969 and a summary of the results of these measurements is shown in figure 6. There was a progressive decline in sediment concentration after the imposition of the special conditions (guidelines) even though wet season rainfall showed very little change, and logging activity continued unabated during each dry season. 1965/66 suspended sediment levels were relatively low because the year's rainfall was 40% below average and very little high intensity rain occurred. The highest suspended sediment level measured during the 1968/69 wet season was only 188 p.p.m. (parts per million) whereas sediment concentrations during the 1965/66 wet season frequently exceeded 700 p.p.m.

It is clear that relatively simple regulations or guidelines - in the form of "conditions" in timber sale agreements in this case - can make a marked improvement in soil erosion and stream sedimentation condition, even in a "patching-up" operation as the rainforest example just described. They can be far more effective if the logging operation is pre-planned and soil and water values are considered from the beginning. This has been shown in numerous studies, mainly in the United States, e.g. 8, 9 and 16.

6. PROBLEMS OF CHANGING THE LOGGING "CONDITIONS" AND ESTABLISHING GUIDELINES

It is generally easier to include "conditions" ("conditions" referring to restrictions, guidelines, specifications, etc) in timber sale agreements than to get them applied. Field operators (both public forestry and private) tend to be very conservative and resist change. It is reasonably easy to convince both the forestry profession and timber industry leaders of the need for change. This awareness has then to be passed on to the people in the field who are actually doing the job - forest rangers and overseers, timber cutters and haulers. This is probably the most difficult part and it requires great patience and perseverance by the supervisors. If the supervisors do their jobs well and convince the field operators of the benefits of the changed conditions, the time will come when field personnel will be conscious of water and soil values as well as timber values and will automatically "do the right thing".

7. CONCLUSIONS

The present climate of environmental concern makes it necessary to make a critical appraisal of our current logging techniques, whether for special areas (such as domestic supply catchments) or for "run of the bush" operations. We should look at utilization from a different point of view; instead of attempting to maximise the return from timber, the aim should be to maximise the overall value of the area for society. This may mean that the return from timber has to be reduced (or even eliminated) from certain areas to take account of other values.

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XIV.

REDUCING EROSIONAL IMPACTS OF ROADS

by

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1. INTRODUCTION

Accelerated erosion may take place following road construction on forested lands. Some possible causes include: (a) removal or reduction of protective cover; (b) destruction or impairment of natural soil structure and fertility; (c) increased slope gradients created by construction of cut and fill slopes; (d) decreased infiltration rates on parts of the road; (e) interception of subsurface flow by the road cut slope; (f) decreased shear strength, increased shear stress, or both, on cut and fill slopes, and (g) concentration of generated and intercepted water.

Numerous reports substantiate the fact that road construction can accelerate erosion on forested lands (1, 2, 4, 6, 9, 14, 15, 18, 19, 20, 22, 24). Experience by FAO in developing countries has often shown that roads are the major source of erosion. As might be expected, effects vary considerably depending on the geologic, climatic, landform, soil, and vegetation properties of the area or country in question and upon the care taken to reduce erosion in all phases of the road development project. Roads constructed on glaciated, metamorphic parent materials in Colorado, for example, exhibited slight accelerated on-site erosion, but no significant increases in sediment yields were detected downstream (14). In contrast, construction of low standard, temporary logging roads on high erosion hazard granitic slopes in Idaho greatly accelerated on-site surface and mass erosion, causing downstream sediment yields to increase an average of over 45 times (from 8.8 to 396 metric tons/km^2/yr) for a 6-year study period (19).

The impacts of road erosion are many. The most direct is to the road itself; excessive erosion can, and often does inhibit road use or even make the road impassable until restored, often at great expense. Less obvious, but often more important, is the movement of eroded material off the site. This can cause sedimentation which may create excessive damage to downstream cultural and ecological values.

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Table 1 – Effect of harvest system and silvicultural practices on the percent area disturbed by road construction (reference 25).

Logging system – Silvicultural system	Logged area bared by road construction	Location	Reference
	%		
Jammer 1/ – Group selection	25–30	Idaho	(19)
High lead 2/ – Clearcut	6.2	Oregon	(26)
Skyline 3/ – Clearcut	2.0	Oregon	(3)
Helicopter 4/ – Clearcut	1.2	–	–

1/ Jammer – a small, truck-mounted skidder-loader – maximum reach about 60 m.

2/ High lead – a cable system that drags logs to the loading area – maximum reach about 200 m.

3/ Skyline – a cable system that suspends logs during transport to the loading area – maximum reach about 800 m.

4/ Estimated by Virgil W. Binkley, Pacific Northwest Region, U.S. Forest Service, Portland Oreg., based on a maximum flying distance of about 1.5 kilometers.

2. EROSION PROCESSES

Recognition of the type of erosion occurring on an area and knowledge of factors controlling erosion are important in avoiding problem areas and in designing control measures. Erosion can be broadly classified into two types - mass erosion and surface erosion. Mass erosion includes all erosion where particles tend to move en masse primarily under the influence of gravity forces. It generally includes various types of landslides plus nonrainfall associated erosion (dry creep). Surface erosion is defined as movement of individual soil particles by forces other than gravity alone such as overland flow of water and raindrop impact. Here, dry creep will be considered a surface erosion process because many soil stabilization measures designed to control surface erosion are also effective in controlling dry creep.

Surface erosion is a function of three factors: (a) the magnitude of forces available (wind, raindrop splash, overland flow, etc.); (b) the inherent erosion hazard at the site in question (soil detachability characteristics, slope gradient, etc.); and (c) the amount of material available to protect the soil surface (vegetation, litter, mulches, etc.). Mass erosion is controlled by the balance between the shear strength and the shear stress within the soil or fill material at the site in question; as long as shear strength exceeds shear stress, the site remains stable.

3. BASIC PRINCIPLES

Fortunately, the erosional impacts of road construction need not be passively accepted; there are a variety of practices available to reduce impacts. These can be summarized as four basic principles:

(1) Minimize the amount of disturbance caused by road construction by: (a) controlling the total mileage of roads; and (b) by reducing the area of disturbance on the roads that are built.

(2) Avoid construction in high erosion hazard areas.

(3) Minimize erosion on areas that are disturbed by road construction by a variety of practices designed to reduce erosion.

(4) Minimize the off-site impacts of erosion.

All four factors must be weighed to reduce total erosional impacts. This is important because stress on individual factors may not meet this goal. For example, a shorter road may have to be lengthened to avoid high erosion hazards. In this case, total erosional impacts may be minimized although the area disturbed is increased. Erosion control practices are certainly beneficial and considerable effort has been and should be devoted to their development and implementation. However, prevention, rather than control, usually is by far the most efficient means to reduce erosional impacts. Prevention can have an added benefit by avoiding possible irreparable damages or costly repairs that may exceed original construction costs.

The first basic principle emphasizes measures designed for erosion prevention rather than control. Minimizing road mileage and areas of disturbance help reduce erosional impacts considerably. This is particularly true on forested lands where the total length of road required is often regulated by the distance capabilities of logging systems and the silvicultural practices prescribed for the timber stands (Table 1).

Reductions in the area disturbed by road construction can also be made by careful road location and design. For example, use of flexible horizontal and vertical alignment standards during road location to avoid steep slopes can decrease the width of area disturbed considerably. To illustrate, total width of disturbance by a road 4 m wide

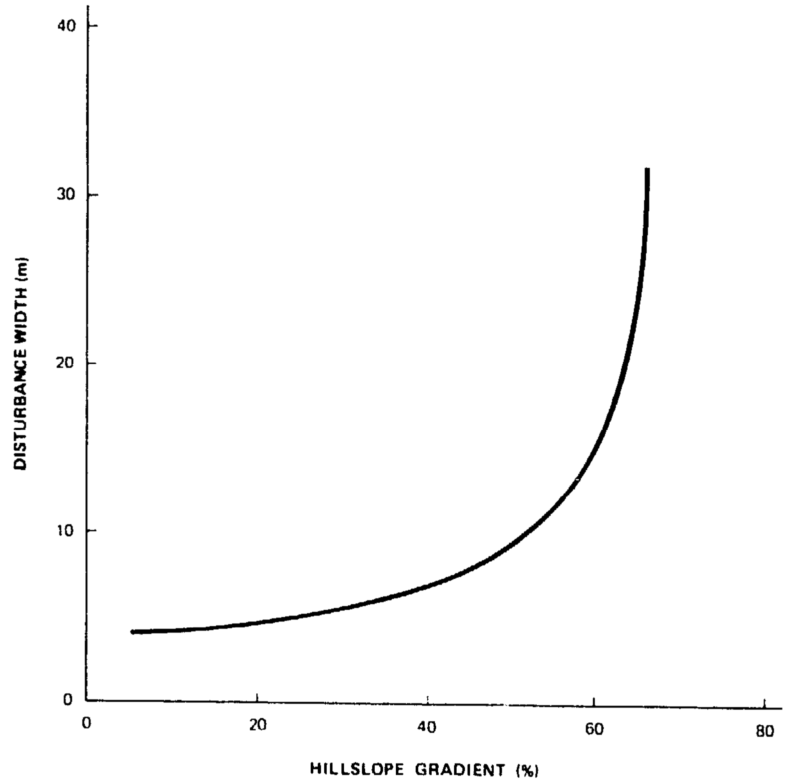


Figure 1. Width of disturbance (projected to a horizontal plane) caused by road construction as a function of hillslope gradient. Assumptions: road width, 4 m; fill slope gradient, 67% (1.5:1); cut slope gradient, 200% (0.5:1); volume of material removed from cut = volume of material in fill ("balanced construction").

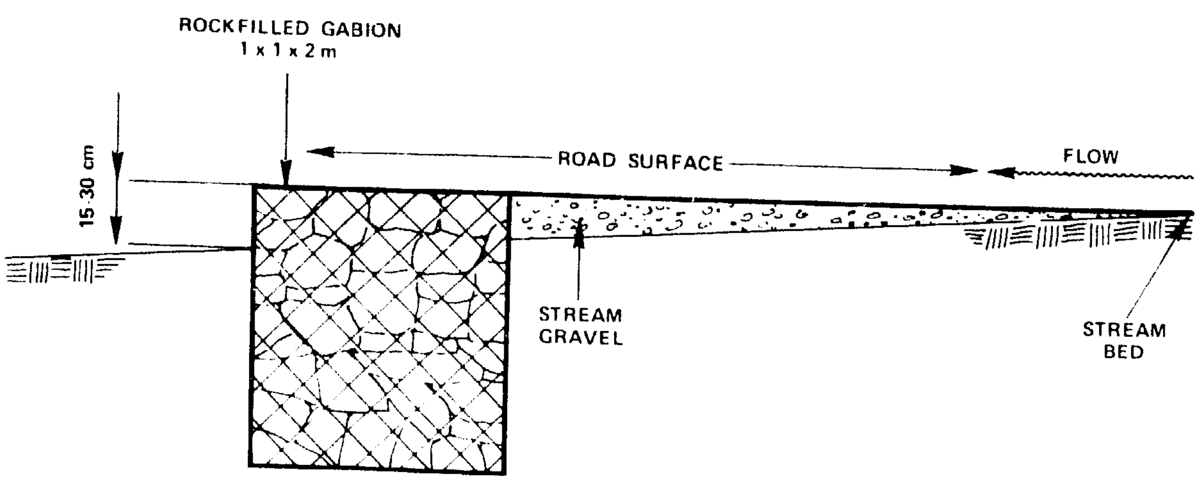


Figure 2. Ford construction stabilized by gabions placed on the downstream end.

increases from about 7 m on a 40% slope to 16 m on a 60% slope; on a 65% slope the width increases to 32 m (Fig. 1). For a given slope, additional reductions in area disturbed can be made by minimizing road and ditch width and by maximizing the gradient of cut and fill slopes (assuming the steeper slopes do not increase other erosion hazards).

The second basic principle for reducing road erosion impacts is another matter of prevention rather than control and consists simply of avoiding high erosion hazard areas. Examples of serious erosion problems caused by road construction in high erosion hazard areas are common, especially where landslide hazards are high. Here even minor location changes of 10 or 20 m may eliminate a major erosion problem. Usually, problems of this type arise from adoption of, and strict adherence to, traditionally accepted road standards (e.g., alignment standards for speed purposes) rather than providing some flexibility in standards to allow the road location to be adjusted to the site properties of the particular landscape in question.

The third basic principle is to reduce erosion on the areas that are distrubed by road construction. This is the traditional approach using a multitude of practices to help reduce erosion. Successful design of erosion control practices requires considerable knowledge of erosion processes, including the major type of erosion that is occurring and the individual factors that control erosion. To illustrate, little benefit results from attempting to stop mass erosion by mulching or surface erosion by installing subsurface drains. Likewise, mulching a road fill slope may have little value if improper design, failure of the road drainage system, or both, cause large quantities of water to flow over the fill.

The fourth basic principle for reducing erosional impacts is to minimize the off-site impacts of erosion that does occur. Essentially this amounts to reducing sediment delivery to stream channels by: (a) keeping disturbed areas as far from channels as possible, (b) providing a maximum of obstructions to catch and retain sediment before it reaches the drainage system, and (c) recognizing that the efficiency of a downslope area to deliver sediment varies considerably depending upon its form and structure.

4. GUIDELINES FOR REDUCING EROSIONAL IMPACTS OF ROADS

These guidelines are based upon the four basic principles which have been described above. They are presented in the context of the entire road development process proceeding from broad land use planning through road location, design, construction, maintenance, and closure. Presentation in this manner is not intended to restrict the guidelines to those higher standard roads receiving such formal step-by-step development. To the contrary, the basic erosion control principles apply to any road development and should be used throughout the development process regardless of the intended purpose or standard of the road.

The guidelines are not all inclusive, but rather are based upon concepts and techniques that have been applied in the temperate climates of the United States. They were developed from experience and research mostly in mountainous terrain. Many of the principles and procedures in this paper will be useful in other areas; however, modifications will undoubtedly be needed to accommodate unique site conditions found in a particular location. Therefore, it is important to verify applicability with local experts (e.g., engineers, land use planners, soil scientists, hydrologists, foresters, geologists) before applying the guidelines.

Much of the material presented here was abstracted from references (7), (10), (11), (12), (13), (21), (28), (29), (30), (31), (32), (33), (34), (35), (36), (37), and (38). The author acknowledges the excellent work of the various authors and institutions and recommends the original references for more in-depth consideration. Undoubtedly, many other excellent references have been developed and should be used where applicable.

5. LAND USE PLANNING

Land use planning with respect to road construction simply means anticipating the present and future uses of the transportation system to assure a maximum of service with a minimum of monetary and erosional costs. The objective of this phase of the road development process is to establish specific objectives and prescriptions for road development along with the broad location needs. This must be a coordinated effort among the land manager, road engineer, forester, geologist, soil scientist, and others who recognize specific problems and needs and recommend alternatives or solutions.

Land use planning is an important factor governing the total area disturbed by road construction. It is particularly important on forested lands where the total mileage of roads constructed is closely related to the timber harvest systems and silvicultural practices prescribed. Harvesting methods also affect the area of disturbance because width and alignment requirements vary with the type of practice used. Additional decisions related to all anticipated traffic, operating speeds, and safety requirements should be made at this time. All of these influence road width and alignment, which affect area of disturbance.

Future as well as present needs must be considered during the land use planning phase. This will help to avoid situations where the road is inadequate for future needs as, for example, in timbered areas where the road network is improperly located for second or third cuts.

The land use planning phase is the time to evaluate environmental and economic tradeoffs. This should set the stage for the remainder of the road development process. If an objective analysis by qualified individuals indicates serious erosional problems, then reduction of erosional impacts should be a primary concern. In some areas, this may dictate the method of land use for the area or may in fact eliminate a land use because reduction of erosional impacts is economically impossible at the time.

6. ROUTE RECONNAISSANCE AND LOCATION

Armed with the guides and constraints developed during the land use planning process, the next step is to determine the specific road location. Alternative routes should be carefully reviewed in the office and at the site, utilizing all available background information (soil surveys, etc.) and technical expertise. Some important guidelines to help reduce erosional impacts during road location are:

1) Avoid high erosion hazard sites, particularly in areas where mass erosion is a problem. In such areas, slight location changes can often eliminate a major erosion problem.

2) Minimize the area of road disturbance by taking advantage of terrain features such as natural benches, ridgetops, and lower gradient slopes.

3) If necessary, include short road segments with steeper gradients (consistent with traffic needs) to avoid problem areas or to take advantage of terrain features.

4) Avoid midslope locations on long, steep, unstable slopes, especially where bedrock is highly weathered or soils are plastic.

5) Locate roads on well-drained soils and rock formations that tend to dip into the slope; avoid slide prone areas characterized by seeps, clay beds, concave slopes, hummocky topography, and rock layers that tend to dip parallel to the slope.

6) For timber harvest roads, take advantage of natural log landing areas (flatter, better drained, open areas) to reduce soil disturbance associated with log landings and temporary work roads.

7) Avoid undercutting unstable, moisture laden toe slopes when locating roads in or near valley bottoms.

8) Vary road grades where possible to reduce concentrated flow in road drainage ditches and culverts and to reduce erosion on the road surface.

9) Select drainage crossings to minimize channel disturbance during construction and to minimize approach cuts and fills.

10) Locate roads far enough above streams to provide an adequate buffer area or be prepared to catch sediment moving downslope below the road. A number of guides have been developed for establishing width of buffer areas based upon hillslope gradient, parent material, cross drain spacing, etc. (e.g., 23, 27). The guide developed by Packer (23) is presented as Table 2.

7. ROAD DESIGN

Road design involves translating field location survey and other data into specific plans to guide construction. Design criteria must be flexible to allow for modifications to minimize erosion hazards under varying site conditions. This is the stage of development where various measures to control erosion and reduce off-site erosional impacts are incorporated into the road design.

Revegetation and associated practices are important considerations during the design process. In addition, future maintenance needs are an important consideration to assure stability and economical use of the completed road. If regular maintenance cannot be assured, this must be accounted for in the design so that undue erosion will not occur.

A number of possible erosion control practices can be included in the road design process:

1) Use as narrow a road as possible commensurate with traffic speed and safety requirements and erosion hazards. In certain situations it may be necessary to reduce speeds and provide for alternative safety measures (e.g., restricted road use) to assure a narrow road in high erosion hazard areas.

2) Attempt to balance the volume of cut and fill material to minimize excavation. Use proper layer placement and compaction techniques wherever possible on fills to assure stability against mass failure.

3) Use full bench construction (no fill slope) where stable fill construction is impossible. Haul excavated material to safe disposal areas. Include waste areas in soil stabilization planning for the road.

4) Where full bench construction is impractical, properly designed retaining walls provide an effective but costly alternative to hold fill material.

5) Use the steepest slopes possible on cut and fill slopes commensurate with the strength of the soil and bedrock material as established by an engineering geologist or other specialist in soil mechanics. Benching cut slopes in areas of weak or erodible bedrock (e.g., weathered granites) into a series of properly drained terraces provides opportunity for vegetation establishment and may even require less excavation.

6) Properly designed road surfacing is often required to prevent excessive roadway erosion and maintain a usable road. The surface required depends on many factors such as the type and volume of traffic, strength of subgrade, service life, and materials available. Often, locally available gravels or crushed rock will serve the purpose. It may be desirable to surface both the road tread and the ditch in one operation.

Table 2 - Protective-strip widths required below the shoulders 1/ of 5-year old 2/ logging roads built on soil derived from basalt, 3/ having 9 m cross-drain spacing, 4/ zero initial obstruction distance, 5/ and 100% fill slope cover density. 6/

Obstruction spacing	Protective-strip widths by type of obstruction					
	Depressions or mounds	Logs	Rocks	Trees and stumps	Slash and brush	Herbaceous vegetation
	Meters					
0.3	10.6	11.2	11.6	12.1	12.5	13.1
.6	11.3	12.2	13.1	14.0	14.9	15.9
.9	11.9	13.1	14.3	15.9	17.4	18.6
1.2	12.2	14.0	15.9	17.7	19.5	21.3
1.5	12.5	14.6	17.0	19.2	21.6	23.8
1.8		15.2	18.0	20.7	23.5	26.2
2.1		15.9	18.9	22.2	25.6	28.7
2.4		16.2	19.8	23.5	27.1	30.8
2.7		16.5	20.4	24.7	29.0	32.9
3.0				25.9	30.5	35.1
3.4				27.8	31.7	36.9
3.7						38.7

1/ For protective-strip widths from centerlines of proposed roads, increase widths by one-half the proposed road width.

2/ If storage capacity of obstructions is to be renewed when roads are 3 years old, reduce protective-strip widths 7 m.

3/ If soil is derived from andesite, increase protective-strip widths 30 cm; if from glacial silt, increase 1 m; if from hard sediments, increase 2.4 m; if from granite, increase 2.5 m; and if from loess, increase 7 m.

4/ For each 3 m increase in cross-drain spacing beyond 9 m, increase protective-strip widths 30 cm.

5/ For each 1.5 m increase in distance to the initial obstruction beyond zero (or the road shoulder), increase protective-strip widths 1.2 m.

6/ For each 10% decrease in fill slope cover below a density of 100%, increase protective-strip widths 30 cm.

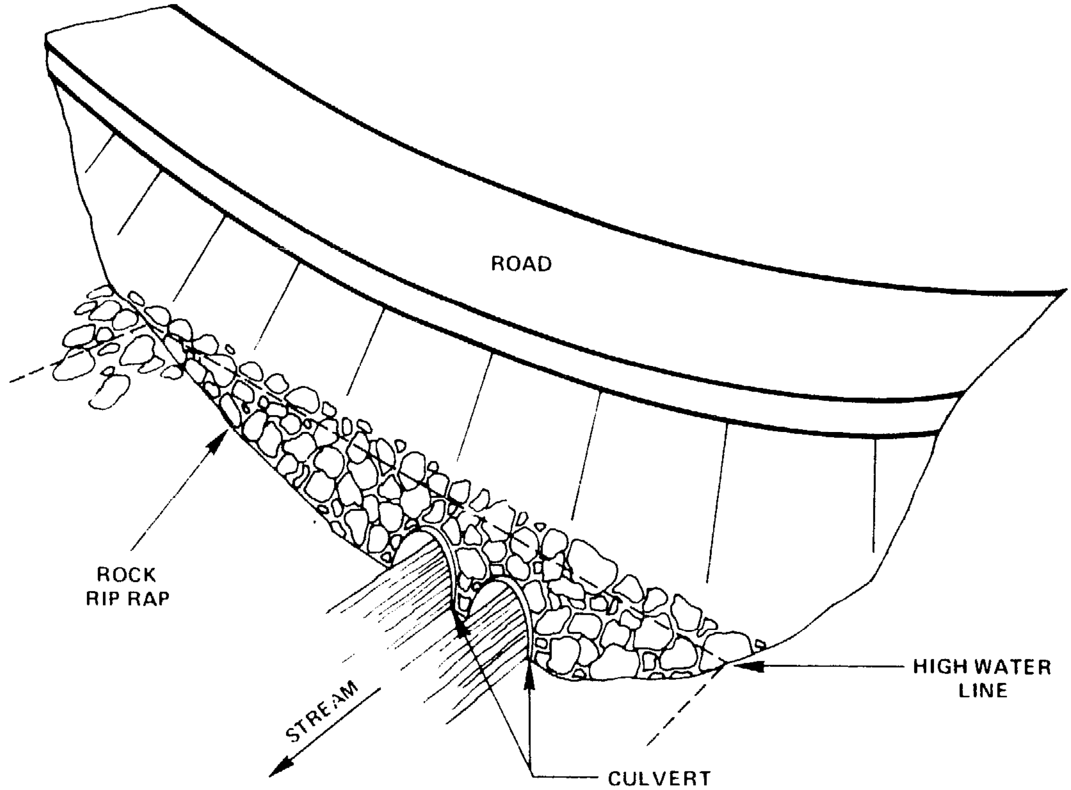


Figure 3. Rock rip-rap protection for embankment at a culvert installation.

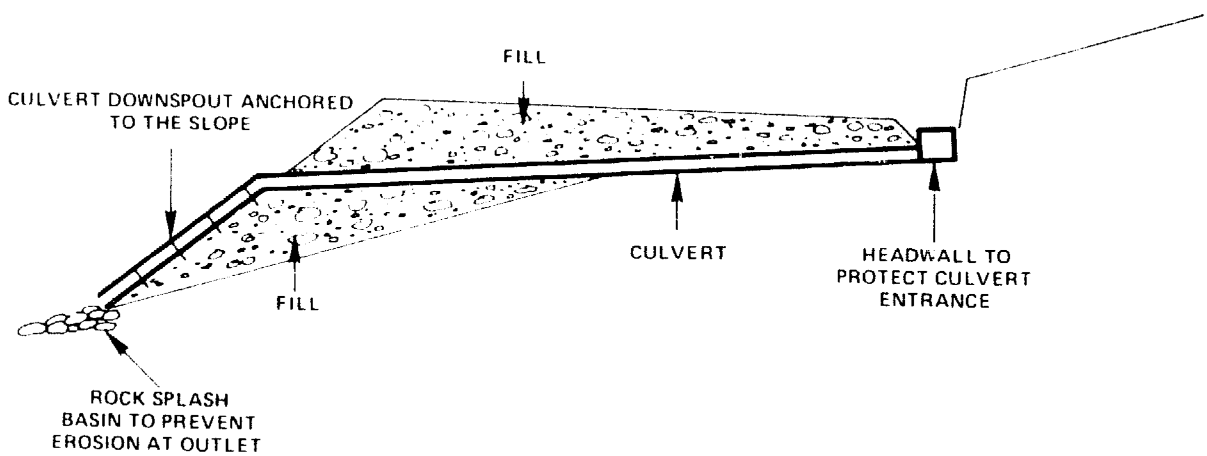


Figure 4. Culvert installation illustrating the use of a headwall, downspout, and a splash basin at the downstream end.

7.1 Road drainage

7.1.1 Crossing natural drainageways

There are three methods for crossing natural drainageways: fords, culverts, and bridges. Factors influencing the appropriate crossing include construction and maintenance cost, equipment and supplies available, debris potential, stream size, contemplated road use and life, foundation conditions, and vertical position of the road relative to the stream.

1) Fords are attractive alternatives for crossing small streams, particularly in areas where large amounts of rock, sediment, and organic debris tend to plug bridges or culverts. Fords cause minimal disturbance to the stream channel, are inexpensive, and avoid many of the problems associated with bridge and culvert installation. Fords require stable channel bottoms able to support vehicles or channels that can be protected by gabions or paving (Fig. 2).

2) Culverts (metal or wood) or bridges are required for channels where fords are impractical. Availability of construction equipment and materials, size of stream, potential for debris, terrain steepness, and reliability of the calculation for determining culvert capacity are some of the points to consider when deciding whether to use a culvert or a bridge at a given location. Other factors being equal, bridges are preferable, particularly in areas with debris or excessive sediment problems because the chances of failure are less.

   Structures should be large enough to carry the flows to which they are subjected within acceptable limits of risk. Costs increase rapidly with size so adequate local hydrological studies are needed. It is important to base the size requirement on the anticipated risk of failure rather than on the return interval of the flow alone (Table 3). The percent chance of failure established for a given structure will depend upon the anticipated economic and environmental hazards.

3) Roads should climb away from channel crossings in both directions wherever practical so high water will not flow along the road surface. Surface sloped sections of the road if necessary to reduce sediment movement directly into the stream.

4) Where adequate maintenance can be assured, install open top culverts or dips in the road surface to direct road runoff on to filter strips rather than directly into the stream.

5) Use rip-rap (placed rock), masonry headwalls, or otherwise protect embankment and channel sides at drainage structures (Fig. 3).

6) Increase the capacity of bridges or culverts in areas where debris, sediment, or both types of problems exist. In extreme situations, this may mean doubling the capacity of the structure.

7) Frequently maintained trash racks (grates) over the inlet end may be useful where floating debris tends to plug culverts.

8) If at all possible, use bridges in areas where debris problems are severe and fords are impractical. Otherwise it may be necessary to construct rock - or gabion-protected fills with a dip to allow overflow in the event that culvert capacity is lost.

7.1.2 Drainage along the roadway

Drainage is needed along the roadway to remove water before it has a chance to concentrate and cause erosion. To help accomplish this, slope road surfaces laterally either outward or inward, depending on traffic needs and erosion hazards. Unfortunately, traffic can cause some rutting in the road surface that concentrates flow along the road in spite of the outsloping or insloping. Thus in many situations, additional cross-drainage measures are needed to interrupt this flow and divert it laterally before it has a chance to cause erosion problems.

Table 3 - Design flood recurrence intervals (years) needed to provide a given project life with a given chance of failure 1/

DESIGN LIFE (YEARS)	Percent chance of failure																		
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
5	98	48	32	23	18	15	13	11	9	8	7	6	6	5	5	4	4	3	3
10	*	96	63	46	36	29	24	21	18	15	14	12	11	9	8	7	6	5	4
15	*	*	93	68	53	43	36	30	26	23	20	17	15	13	12	10	9	8	6
20	*	*	*	91	71	57	47	40	34	30	26	23	20	18	15	13	12	10	8
25	*	*	*	*	38	71	59	50	43	37	32	28	25	23	19	17	14	12	9
30	*	*	*	*	*	85	71	60	51	44	39	34	30	26	23	20	17	14	11
35	*	*	*	*	*	99	82	70	60	51	45	39	34	30	26	23	19	16	13
40	*	*	*	*	*	*	94	79	68	59	51	45	39	34	30	26	22	18	14
45	*	*	*	*	*	*	*	89	76	66	57	50	44	38	33	29	25	21	16
50	*	*	*	*	*	*	*	99	85	73	64	56	49	43	37	32	27	23	18
55	*	*	*	*	*	*	*	*	93	80	70	61	53	47	42	35	30	25	19
60	*	*	*	*	*	*	*	*	*	88	76	66	58	51	44	38	33	27	21
65	*	*	*	*	*	*	*	*	*	95	82	72	63	55	48	41	35	29	23
70	*	*	*	*	*	*	*	*	*	*	89	77	68	59	51	44	38	31	24
75	*	*	*	*	*	*	*	*	*	*	95	83	72	63	55	48	41	34	26
80	*	*	*	*	*	*	*	*	*	*	*	88	77	67	59	51	43	36	28
85	*	*	*	*	*	*	*	*	*	*	*	94	82	72	62	54	46	28	29
90	*	*	*	*	*	*	*	*	*	*	*	99	87	76	66	57	48	40	31
95	*	*	*	*	*	*	*	*	*	*	*	*	91	80	70	60	51	42	33
100	*	*	*	*	*	*	*	*	*	*	*	*	96	84	73	63	54	44	34

1/ Based on the formula $J = 1 - (1 - 1/T)^N$, where N = Design Life, T = Flood Recurrence Interval, J = Chance of Failure (reference 5).

* More than 99.

Example: If a culvert through a road is to last for 20 years with a 30% chance of failure, the culvert should be designed for the 57-year flood recurrence event.

Table 4 - Cross-drain spacings required to prevent rill or gully erosion deeper than 2.5 cm on unsurfaced logging roads built in the upper topographic position 1/ of north-facing slopes 2/ having a gradient of 80% 3/ (reference 23, table 2).

Road grade (%)	Material					
	Hard sediment	Basalt	Granite	Glacial silt	Andesite	Loess
	Cross-drain spacing, m					
2	51	47	42	41	32	29
4	46	42	38	37	27	24
6	44	40	35	34	25	22
8	42	38	33	32	23	20
10	39	35	29	29	20	17
12	36	32	27	27	17	15
14	33	29	24	23	14	11

1/ In middle topographic position, reduce spacings 5.5 m; in lower topographic position, reduce spacings 11 m.

2/ On south aspects, reduce spacings 4.6 m.

3/ For each 10% decrease in slope steepness below 80%, reduce spacings 1.5 m.

1) <u>Outsloping</u> (i.e., sloping toward the downhill side of the road) of from 3-5% is preferable to insloping because it eliminates the need to develop facilities to dispose of the water draining down the inside of the road. Outsloping can be unsafe in some situations because of particular traffic requirements or unusual site conditions such as clayey road surfaces that are very slippery when wet. In addition, outsloping should only be used where runoff will flow off the road onto stable surfaces. Normally, this precludes the use of outsloping on fill portions of the road unless fill slopes are small and low in erodibility or are well protected by mulches, vegetation, or both.

2) <u>Insloping</u> (i.e., sloping toward the uphill side) of the road surface is preferred to outsloping in areas of unstable fills, except in the case of a contour road where there is no chance for lateral flow along the road. Water draining from the road is carried along the inside of the road either on the road surface itself or more commonly in a ditch. Culverts are installed periodically to carry the water under the road. Some points to consider when designing an insloped road are:

   a) Avoid using ditches or keep ditches to a minimum width and increase the number of cross drains to reduce the total area disturbed by construction.

   b) Plan ditch gradients steep enough (generally greater than 2%) to prevent sediment deposition.

   c) Install culverts frequently enough to avoid accumulations of water that will cause excessive erosion of the road ditch and the area below the culvert outlet. Surface the ditch in areas of erodible material (e.g., weathered granitics).

   d) Use a culvert size of at least 40 to 50 cm, depending on expected debris problems.

   e) Install culverts at the gradient of the original fill slope if possible: otherwise provide anchored downspouts to carry the water safely across the fill slope. Skew culverts 20° to 30° toward the inflow to provide better inlet efficiency and flow characteristics. Provide rock or other splash basins at the downstream end of culverts to reduce the erosion energy of the emerging water (Fig. 4).

   f) Protect the upstream end of culverts from plugging with sediment by using sediment catch basins, drop inlets, changes in road grades, headwalls, and recessed cut slopes.

   g) Install the culvert deep enough to assure that it will not be crushed by traffic loads. This requires a depth of about 1.2 m for metal culverts subjected to loads from large, loaded logging trucks.

3) In some areas, alternating inslope and outslope sections can be built into the road, especially if road grades are "rolled" (provide alternating adverse and favorable grades). In such instances, install dips or cross drains on the surface of the road to control erosion of the roadway.

4) It is usually necessary to construct cross drains in the road surface on either insloped or outsloped roads to help prevent erosion caused by water concentrations in ruts. Various types of cross drains are used, including open-top culverts and intercepting dips. Some points to consider when installing cross drains are:

   a) Spacing requirements - spacing depends on a number of factors such as road grade, and type of material. Guides for spacing are presented in Table 4.

   b) Open-top culverts are usually constructed of wood (Fig. 5). They should be installed at a 30° angle downslope to promote self cleaning and make crossing easier (Fig. 6). Culverts of this type <u>must</u> be properly maintained to prevent plugging and damage by traffic.

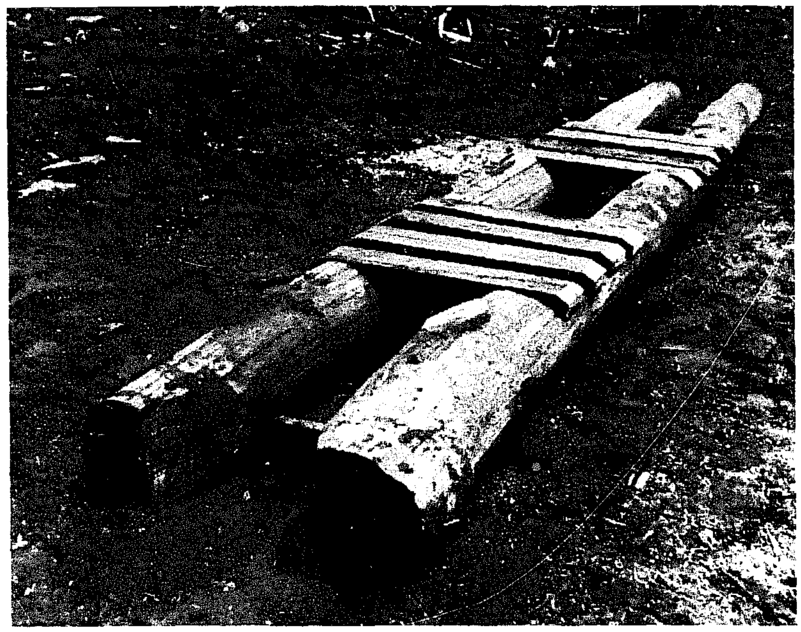


Figure 5. An open-top culvert constructed of wood. Spreaders on the bottom of the logs maintain culvert shape and the 5-cm spaces between the boards prevent water from running down wheel tracks and across the culvert.

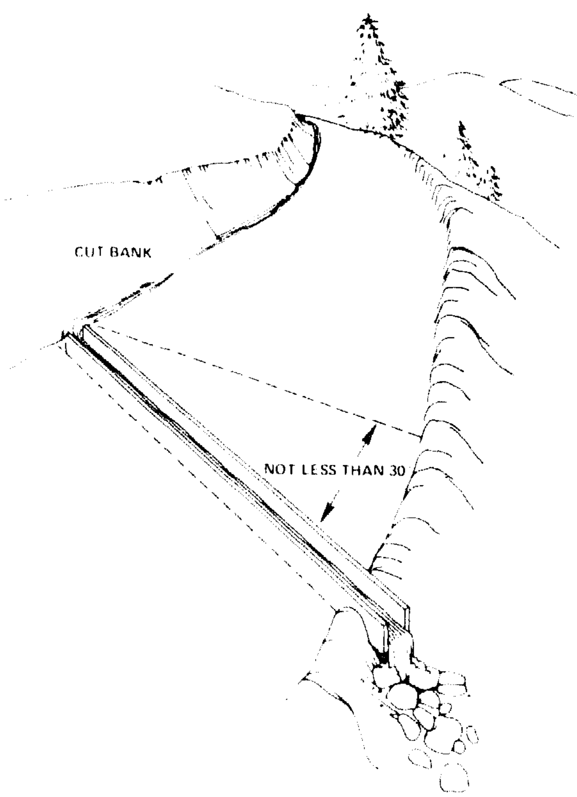


Figure 6. Installation of an open-top culvert. Culverts should be slanted at least 30° downslope to help prevent plugging.

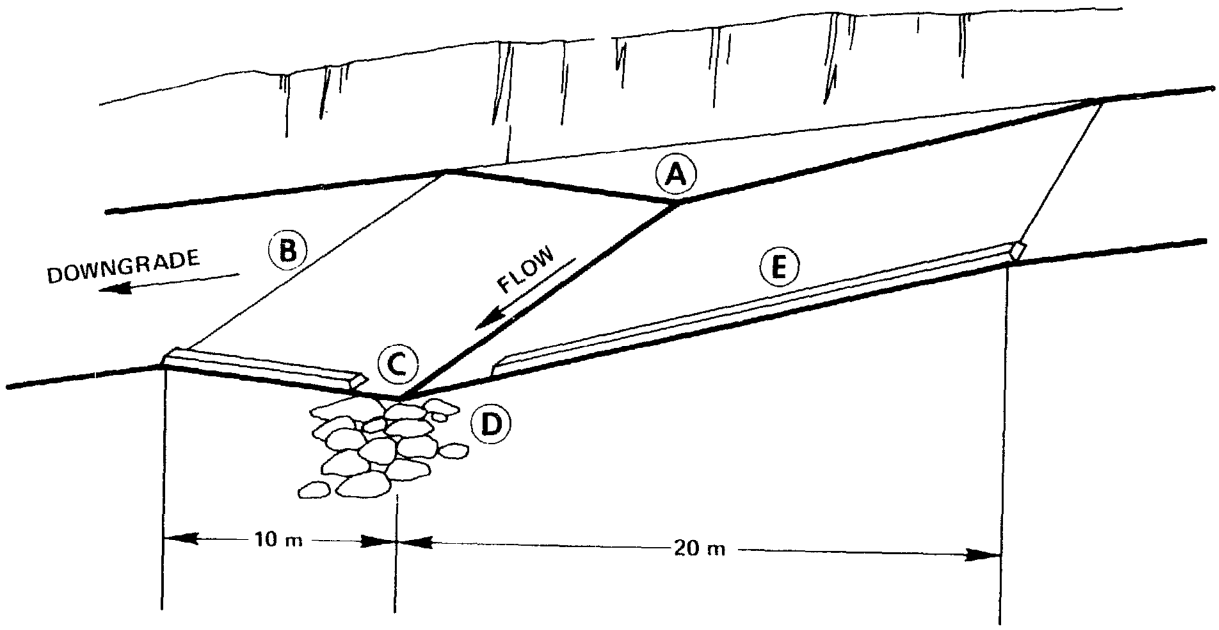


Figure 7. Design of outsloped dips for forest roads. A to C, slope about 10 to 15 cm to assure lateral flow; B, no material accumulated at this point - may require surfacing to prevent cutting; D, provide rock rip-rap to prevent erosion; E, berm to confine outflow to 0.5 m wide spillway.

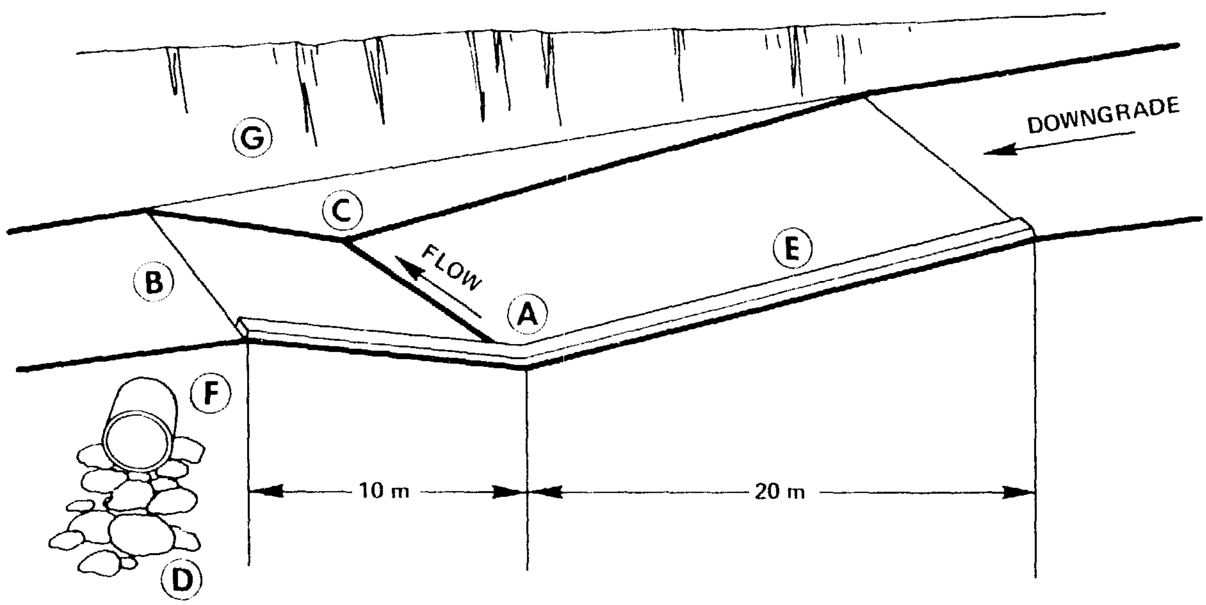


Figure 8. Design of insloped dips for forest roads. A to C, slope about 10 to 15 cm to assure lateral flow; B, no material accumulated at this point - may require surfacing to prevent cutting; D, provide rock rip-rap to prevent erosion; E, berm to prevent overflow; F, culvert to carry water beneath road; G, widen for ditch and pipe inlet.

c) Intercepting dips, when properly constructed, are cheaper to maintain and more permanent than wood, open-top culverts. Dip design depends on the kind and speed of the traffic using the road. The dip designs shown in Figures 7 and 8 allow road use by passenger autos travelling at speeds of approximately 30 kilometers per hour. On steeper roads it may be necessary to install open-top culverts (using the same design) in addition to dips to meet the cross-drainage spacing criteria shown in Table 4. A good discussion of dip design is given in reference 8.

d) In addition to cross drain spacing, location of cross drains is an important factor to consider in minimizing sediment delivery to stream channels from either insloped or outsloped roads. Some location guides are presented in Figure 9.

5) Berms are required on the outside edge of the road at specific locations where alignment and grade characteristics cause excessive runoff from the road tread over the fill slope. Use compacted soil, soil cement, or asphalt mixtures to construct stable berms. Where necessary, use downspouts in the berm to safely carry water to the bottom of the fill slope. Locate downspouts at safe water discharge points and provide energy dissipators (rock basins, etc.) to further reduce erosion hazards (Fig. 10).

8. SLOPE STABILIZATION MEASURES (REVEGETATION AND MULCHES)

Slope stabilization includes revegetation and other measures to control surface erosion on road cut and fill slopes and on waste and borrow areas. Usually the objective is to establish a dense vegetative cover to reduce forces available for erosion and increase surface protection.

Considerable evidence indicates that surface erosion on severely disturbed soils such as road fills is highest immediately after disturbance and decreases rapidly over time. On granitic slopes in Idaho, approximately 80% of surface erosion occurred within the first year following disturbance (16). This suggests two things: (a) it is mandatory that stabilization practices be applied immediately during and following construction; and (b) stabilization practices must provide rapid benefits. Thus, simply seeding disturbed areas may not be acceptable; transplanting or mulching may be required to achieve the desired results.

Stabilization of mass erosion is beyond the scope of this guideline; however, there is considerable evidence suggesting that deep-rooted vegetation (trees and shrubs) acts as a deterrent to mass erosion. Since deep-rooted vegetation also helps control surface erosion, its use is advocated for slope stabilization (17).

Some suggested guidelines for slope stabilization are described below:

8.1 Revegetation

1) Site factors governing air and soil temperature, soil moisture, and fertility are important influences on revegetation success. Large variations in these factors can occur throughout the length of a road, particularly in low precipitation zones or in areas with prolonged dry seasons. Such differences are often magnified in mountainous areas. Thus it is important to tailor revegetation measures to the specific site factors. Consider elevation, aspect, rain shadow effects, ground-water seepage, soil and bedrock properties, etc., in evaluating site differences. Be sure to include vegetation in the evaluation, both as an indicator of site potential and to serve as a guide for species selection.

2) Site preparation is often an important prelude to seeding and planting. This might include various practices such as: (a) spreading previously stockpiled topsoil; (b) chaining, harrowing, disking or rolling to roughen the seedbed and break surface crusting; and (c) fertilizing.

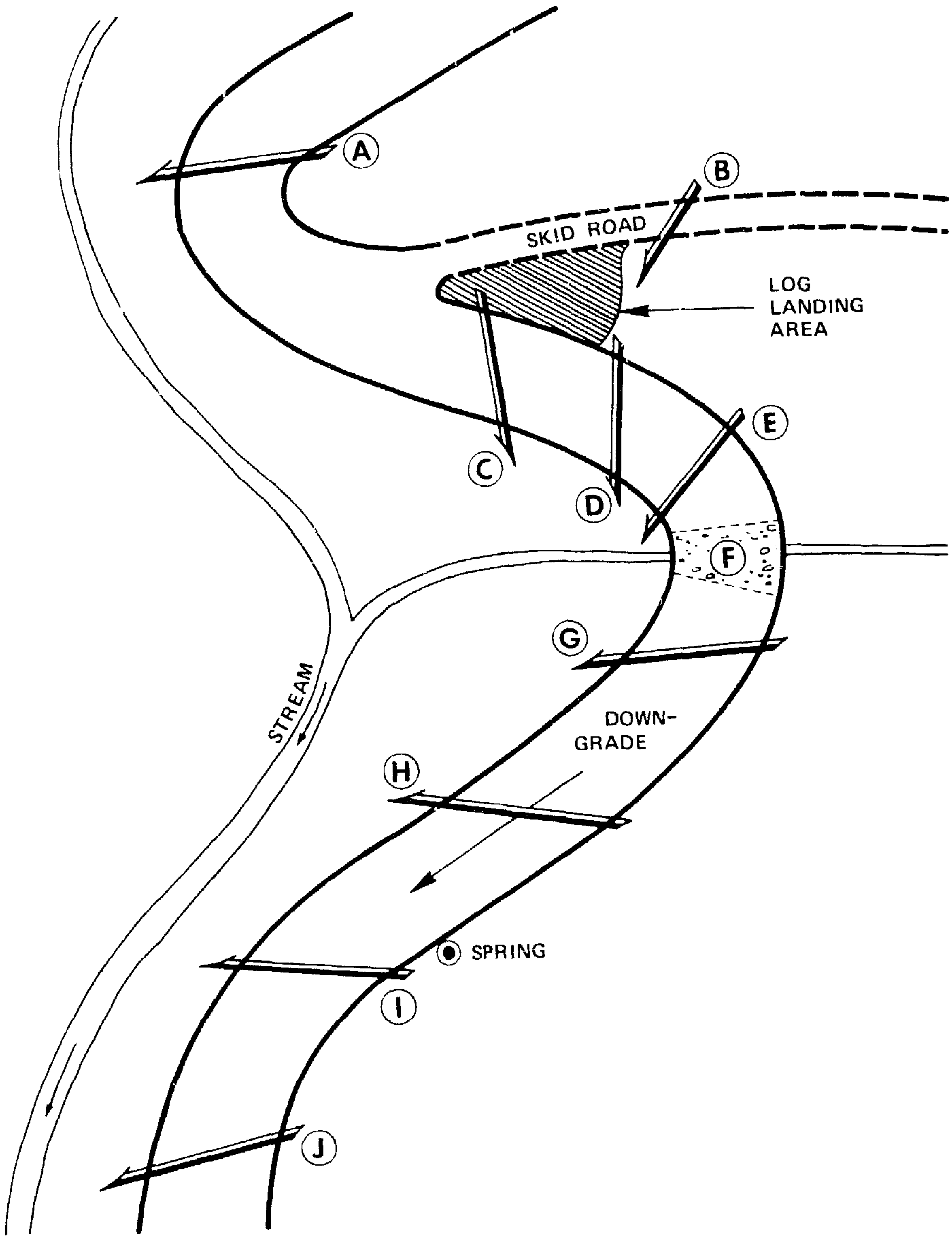


Figure 9. Guides for locating cross drains. Several locations require cross drains independent of spacing guides. A and J, divert water from ridge; A, B and C, cross drain above and below junction; C and D, locate drains below log landing areas; D and H, drains located with regular spacing; E, drain above incurve to prevent bank cutting and keep road surface water from entering draw; F, ford or culvert in draw; G, drain below incurve to prevent water from coursing down road; I, drain below seeps and springs.

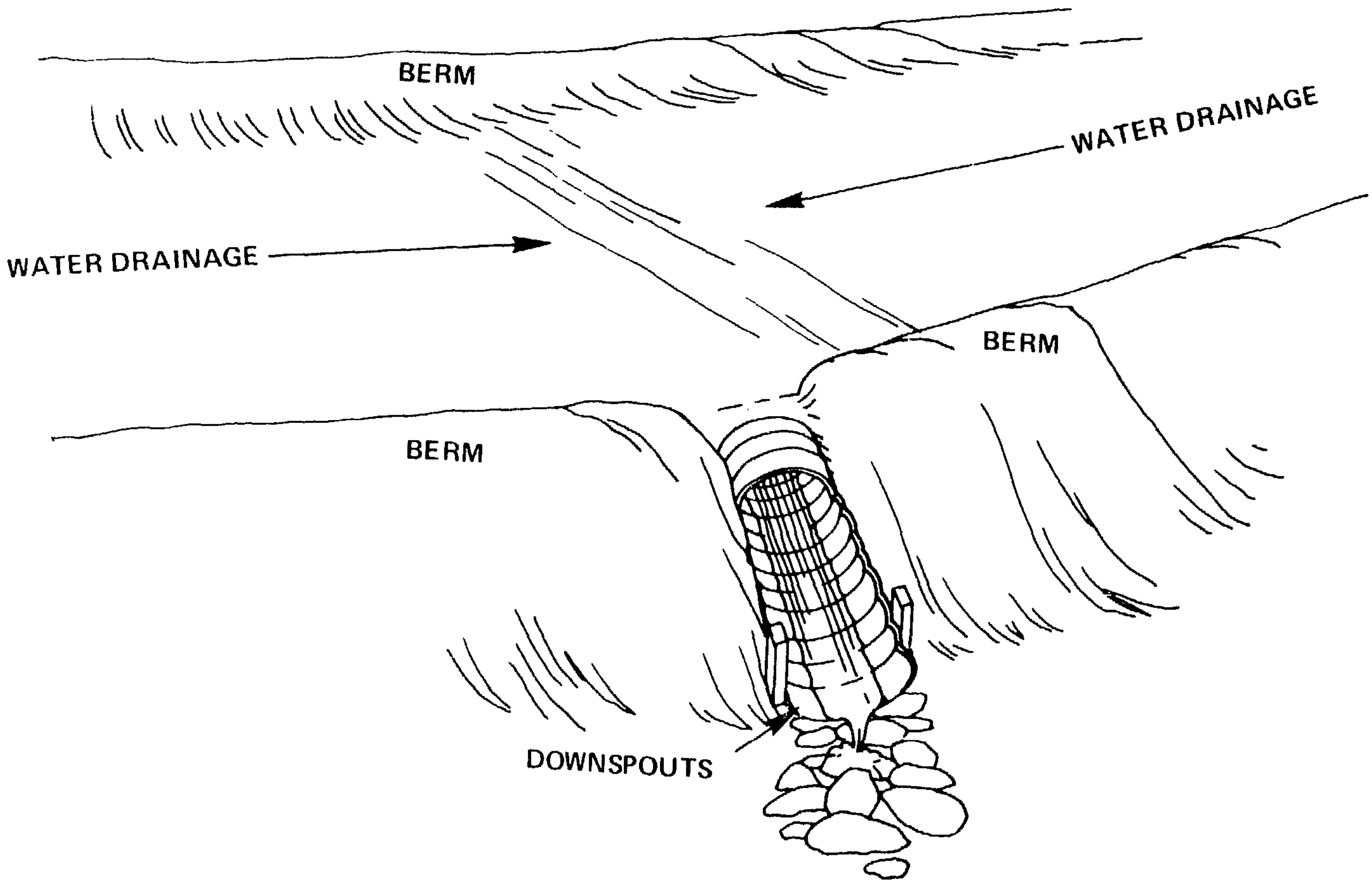


Figure 10. Construction of a downspout in a berm. Excess water accumulations on a berm must be drained by a downspout.

3) It is desirable to conduct seeding operations before mulching to attain maximum benefit from the mulch. However, this is not possible in some locations (e.g., areas with pronounced dry seasons) because the time of seeding or transplanting is critical. To illustrate, many locations on the west coast of the United States are influenced by a distinct Mediterranean climate causing a prolonged drought period in the summer. Seeding and planting operations during the drought period are usually failures; operations must take place in the fall to be successful. Transplanting through a previously applied mulch is often successful in these situations. Sometimes wattling (installing low barriers of soils and brush along the contour up and down the slope) is a successful substitute for mulching. Seeding, planting, or both, between the wattles can then be carried out at the proper time.

4) Species selection must be designed to meet local needs. Grasses have been most commonly used; however, forbs, shrubs, and trees alone or in combinations should be considered. Legumes have particular benefits as nitrogen fixers as do some other plants. Deep-rooted plants including both trees and shrubs can help increase mass stability as well as reduce surface erosion. Rapid-growing, short-lived species (e.g., some of the ryes and oats) are often desirable for nurse crops for slower growing vegetation.

5) Fertilization should accompany most revegetation operations. Proper types and amounts of fertilizer should be based upon soil analyses or experience in the area. Additional amounts may be required if organic mulches are used.

8.2 Mulches

In some areas, vegetation response is rapid enough to provide slope protection during the initial high erosion period. However, it is usually necessary to supplement the protection during the interim with mulches. Mulching provides additional benefits by reducing surface soil temperatures, water losses from the soil, and soil crust formation.

1) Many kinds of materials ranging from logging slash to peanut shells have been used for mulching. Type of material is not as important as the need to use sufficient amounts in close contact with the soil.

2) On steeper areas it is often necessary to anchor the mulch into the soil by covering it with netting material that is pinned in place, spraying adhesive chemicals (e.g., liquid asphalt, various polymers) onto the mulch, or rolling it with a spike roller.

3) Machines have been developed that combine mulching material (straw or wood fibre are commonly used) with water, an adhesive, or both, and spray the mixture onto the slope. Usually, seed and sometimes fertilizers are added to the mixture to provide multi-benefits in one operation.

8.3 Other practices

Other types of stabilization practices have also been used:

1) Recent development of polymers permits stabilization of disturbed areas by spraying the material on the surface.

2) Sometimes revegetation practices increase infiltration of water into the surface sufficiently to increase mass erosion hazards to the point of failure (11). In these cases, an impermeable material (e.g., asphalt, certain polymers, or even plastic sheeting) may be required to stabilize surfaces.

9. CONSTRUCTION

The construction phase is the moment of truth for a road development. The best planning and design is useless unless it is incorporated into the finished product. Competent planning and supervision of the construction phase is probably the single most important factor leading to success. This requires a thorough knowledge of construction methods, equipment, materials, and testing coupled with a sense of diplomacy to communicate with the individuals doing the work. Such a background will not only enable the construction supervisor to develop the road as planned but will also allow him to effectively deal with the inevitable design changes required during construction because of unforeseen circumstances (especially in earthwork and drainage installations).

Some important erosion control practices to consider during construction include:

1) Keep slope stabilization work as current as possible with road construction.

2) A thorough job of clearing and grubbing is required to insure proper construction of fills. Overcasting onto brush and timber or incorporating brush and timber into the fill material can lead to serious surface and mass erosion problems. In addition, provide a good base for fills and assure proper compaction as fills are constructed.

3) Where possible, the cleared vegetation should be spread evenly over the soil surface beneath the toe of the road fill. The vegetation material should be cut up or somehow crushed into the surface to assure close contact with the soil. This practice should enhance the buffering qualities of the slope beneath the road (see Table 2).

4) When installing culverts, avoid channel changes and place culverts so they conform to the natural stream channel as closely as possible. Remove as much debris from the channel above the culvert as possible. Carefully compact the fill material around all culverts to prevent seepage and ultimate culvert failure.

5) Keep stream disturbance to an absolute minimum and avoid it altogether during high flow periods.

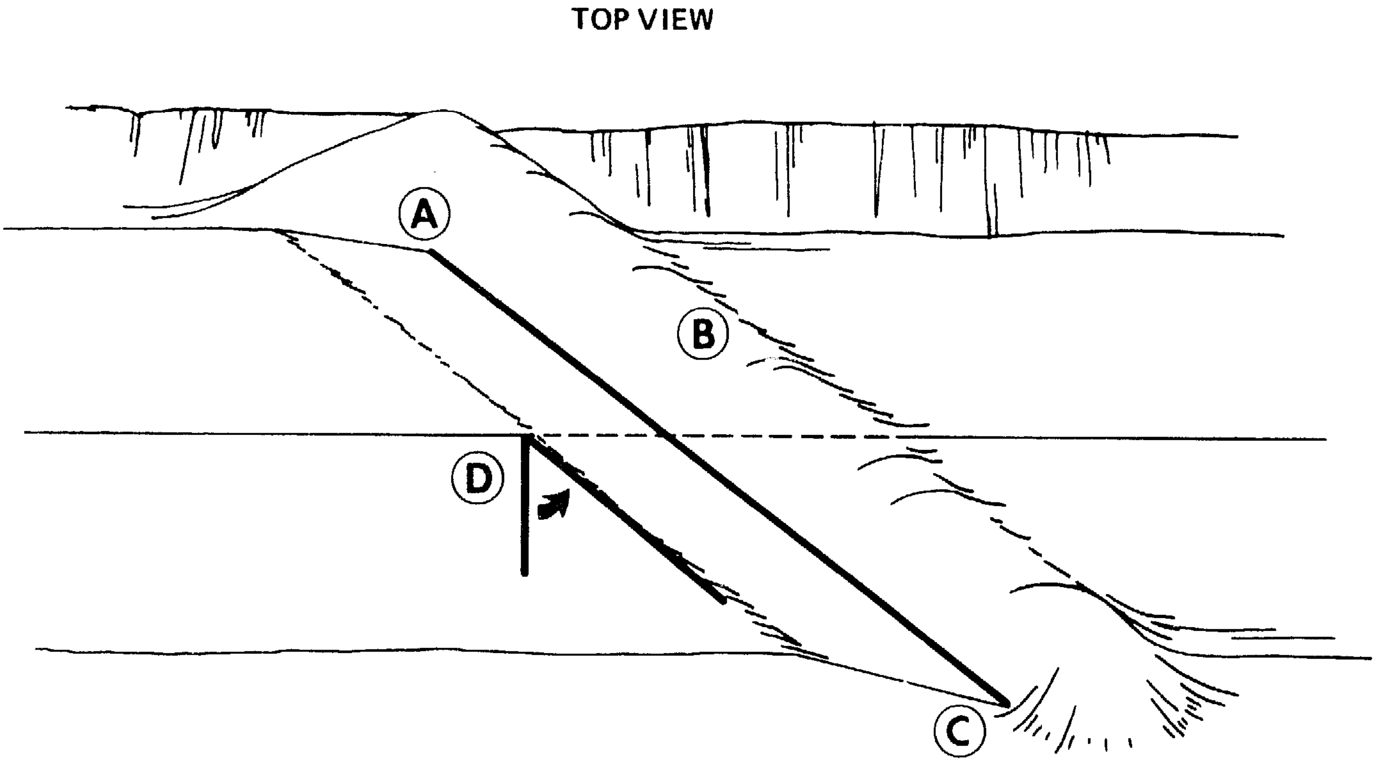
6) Vagaries in weather conditions are an important factor leading to erosion during construction. In areas where the climate permits, plan jobs for completion during dry periods. Elsewhere, limit the work area to small sections than can be completed before proceeding further. This exposes a minimum of disturbed area to erosion forces in the event the weather changes. Light rains usually have limited erosional impacts. However, if obvious impacts occur during larger storms, be prepared to cease operations after installing emergency drainage as needed. It is advisable to install all designed drainage from the downstream end of the job to the upstream end in areas of unpredictable weather.

10. ROAD MAINTENANCE

Diligent maintenance is an absolute necessity to assure effective erosion control throughout the life of a road. Following construction, inevitable deficiencies in design and construction practices require modification or repair. Throughout the life of the road, traffic use and natural deterioration continue to make diligent maintenance a necessity.

Recommended maintenance practices are:

1) A maintenance record should be developed for each road consisting of the actual construction plans for the road and a tally of the kind and cost of maintenance operations required over time. The record will assist in training new personnel and provide a solid background of data to prevent extension of mistakes to roads in other areas.



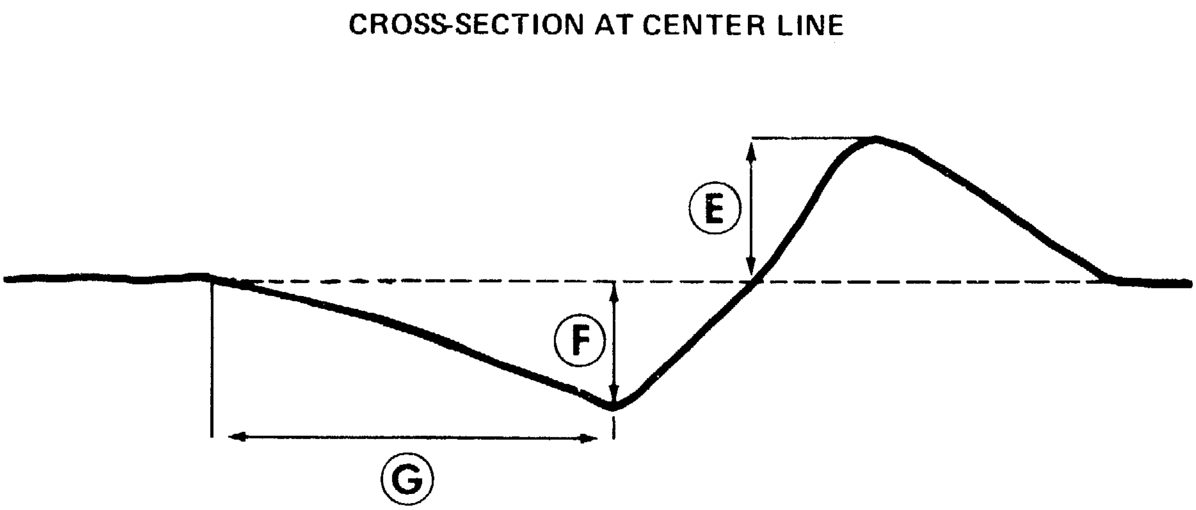


Figure 11. Cross ditch construction for forest roads with limited or no traffic. Specifications are average and may be adjusted to gradient and other conditions. A, bank tie-in point cut 15 to 30 cm into roadbed; B, cross drain berm height 30 to 60 cm above road bed; C, drain outlet cut 20 to 40 cm into road; D, angle drain 30° to 40° downgrade with road centerline; E, height up to 60 cm, F, depth to 45 cm; G, 90 to 120 cm.

2) Culverts, cross drains, and dips should be cleaned regularly to assure proper functioning, especially before winter or expected rainy seasons. Debris should be removed from live drainages for a distance of 30 m upstream from the inlet. Cross drains and dips are often damaged during high use periods or sometimes even removed for more efficient traffic flow; they should be replaced before rainy seasons or snowfall.

3) Ditches should be cleared of debris and sediment accumulations with care being taken to avoid disturbing stabilized ditch bottoms. Avoid undercutting the roadcut when removing slide debris.

4) Grade the road surface as often as necessary to retain the original surface drainage (either insloped or outsloped). Take care to avoid side-casting graded material over the fill slope. Carefully monitor surface drainage during wet periods and close the road if necessary to avoid undue damage. Restore surfacing on the road tread and in the road ditch if necessary following damage caused by operation in wet periods.

5) Haul all excess material removed by maintenance operations to safe disposal areas. Apply stabilization measures on disposal sites if necessary to assure that erosion and sedimentation do not occur.

6) During large storms or excessive snowmelt it is beneficial to patrol roads to assure that road drainage facilities are functioning.

11. ROAD CLOSURE

Many roads, especially work roads associated with timber harvesting, are designed for use only for a short time. These roads should be closed along with any other roads that are needed only for intermittent travel to minimize maintenance expense and erosion hazards. Two possible situations exist: (a) the road should be closed, but use is anticipated in the future; and (b) permanent closure is desired.

11.1 Temporary closure

Steps recommended for temporary road closure are:

1) Block the road to vehicles.

2) Remove all temporary culverts including brush and wood types.

3) Remove all temporary bridges.

4) Remove all other culverts and bridges that cannot be maintained.

5) Except on large fill slopes, outslope the road surface and remove all berms, taking care not to spill graded material over the fill slope. The best way to accomplish this is to grade material toward the cut bank. Outslope only enough to divert water over the bank (approximately 2 to 3% plus the slope gradient of the road in percent).

6) When removing culverts and bridges, be sure all fill material is removed from below the high water line of the stream. All material that is removed should be placed in a safe disposal area. The remaining fill material should be left at a stable angle.

7) Cross ditch the road tread in accordance with the cross ditch design shown in Figure 11, and the cross-drain spacing guides in Table 4 and Figure 9.

8) Revegetate the road surface and areas disturbed by road closure operations along with any other areas of exposed soil. Use all revegetation procedures necessary (including mulching) to stabilize the site.

11.2 Permanent closure

Similar procedures are used for permanent road closure except that all bridges and culverts are removed. In addition, it is also desirable to break up road surface compaction to reduce runoff and provide a better site for revegetation. Ripping with a hydraulic ripper is an effective way to accomplish this. Fill material should be removed from any area where mass failure is possible in the future. Place material in a safe disposal area and use erosion control methods at the disposal area.

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XV.

WATERSHED ORGANIZATIONS AND SOCIO-ECONOMIC FACTORS

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Punjab, India

1. INTRODUCTION

Planning and implementation of a watershed management programme is complex. It requires the collection and analysis of a great deal of information on the physical, biological, economic and social aspects of a region as well as a well-trained staff. The relationships of plants, soil and water to land management are fairly well understood in the developed nations. They are not so appreciated in the developing countries, where vast areas of the world have been laid waste by overgrazing, reckless felling of forests and the farming of sub-marginal lands (Figure 1), with an apparent unawareness of the economic hazards which are created.

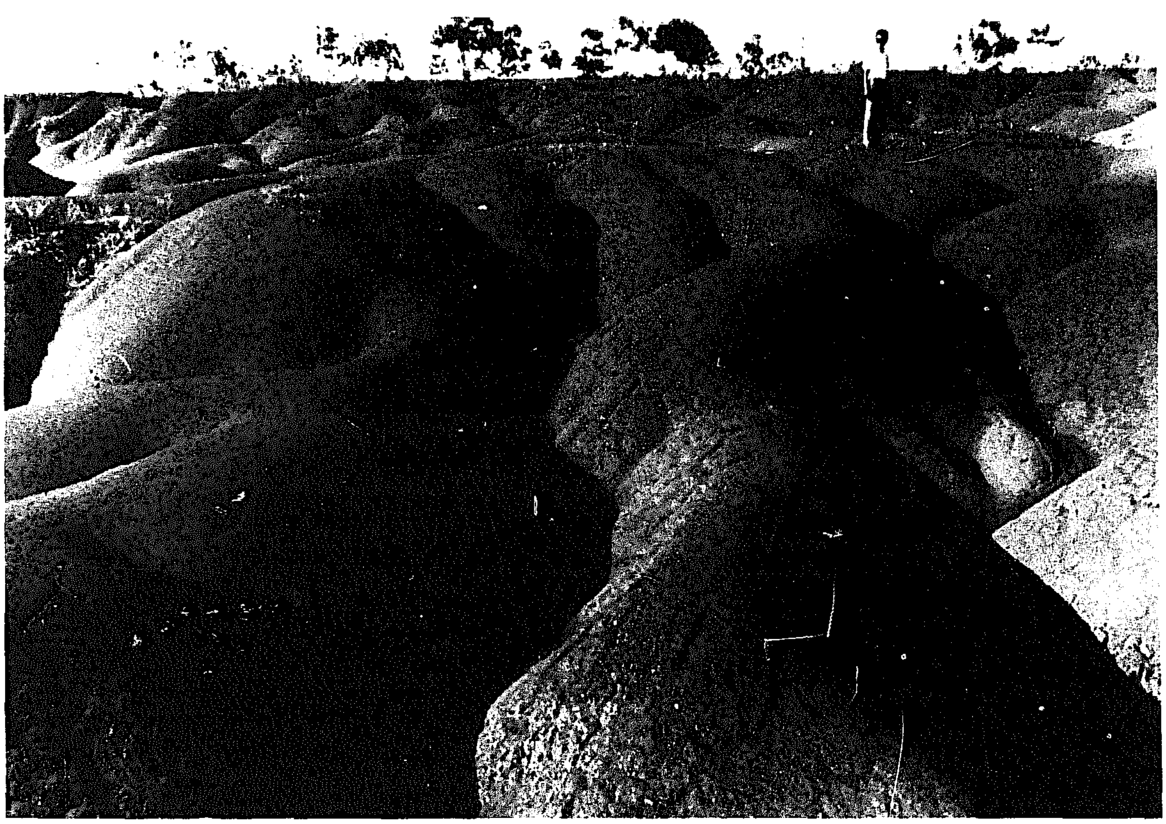


Figure 1. Erosion in Asia is one of the principal problems impeding the development of agriculture and causing flood and sedimentation problems (FAO photo by H. Null, Java, 1971).

1/ Mr. Singh was until recently Chief Conservator of Forests, Punjab, India, 266 Secton 9C, Chandigarh, India.

2. SOCIO-ECONOMIC FACTORS

People are the most important factor in good watershed management. The root cause of watershed degradation in most of the developing nations is the ignorance and economic backwardness of the people and their outmoded social systems.

These lead to:

- Cultivation of poor land without adequate soil and water conservation and of land basically unsuitable for sustained agriculture.

- Spread of shifting cultivation, involving permanent forest land or reduction of forest fallow periods, with soil exhaustion and a replacement of forests by grasslands.

- Deterioration in forest conservancy.

- Overgrazing of forests and grasslands so that vegetation disappears and stone screes and ravines are formed.

- Road building and other land-changing public works without conservation.

As the rural population increases, shifting cultivation spreads further into more fragile lands and even into permanent forest lands. In many cases, the forest fallow period is reduced which results in exhaustion of soils and the replacement of forests by inferior scrub and grass species. This process, combined with fires, is responsible for vast destruction of forests. Laws and regulations have failed to stop shifting cultivation and its rapid growth. It is a socio-economic problem forced by increasing population pressure and the lack of alternative means of livelihood. The problem is further aggravated by political situations in some countries. Similarly, the destruction of forests by fire is also caused by ignorance, deeprooted economic evils and the belief of the forest dweller that fire will produce a fresh flush of green grass, destroy insects and wild life harmful to cattle, drive game into traps or even propitiate the rain gods in times of prolonged drought.

Wars from times immemorial have been responsible for destruction of forest resources. Whenever a forest was suspected of harbouring an enemy, it was deliberately burned to deny a place of concealment. The war refugees are also responsible for burning and clearing the forests for a subsistence form of agriculture. In the example in Indo-China, prolonged war aided by scientific knowledge and modern technological advances has been responsible for an unprecedented scale of forest destruction and environmental damage.

Even in comparatively peaceful and developed regions, failure of the governments to protect forest areas, combined with the generous granting of grazing rights and other privileges, has been responsible for the serious retrogression of forests. The immediate demands of the population frequently are nursed by politicians, who give little attention to safeguarding the environment for the future. Inadequate consideration of the geophysical conditions of a region and the social requirements of the population, compounded by great emphasis on the immediate objectives to increase economic development has often resulted in wasted effort and imbalances between man and his environment.

The concept of comprehensive watershed planning and conservation of natural resources has been generally missing in the developing nations. For example, road construction, intended to develop economically backward regions, has often lacked the soil conservation concept, resulting in the widespread destruction of hillsides. There are also serious organizational limitations and lack of technical and managerial personnel to apply a multipurpose approach for balanced development. Furthermore, there is a general absence of vocational education in forestry, agriculture, animal husbandry, soil conservation and water management in the developing countries and little research to deal with the problems affecting watershed conditions.

3. NEED FOR WATERSHED ORGANIZATIONS

Laws, regulations and controls have generally failed to stop shifting cultivation, subsistence agriculture or overgrazing. No pious hopes can force shifting cultivators to give up their destructive practices unless alternative means of livelihood are provided that are also acceptable to the communities. In addition to finding technical solutions of watershed problems, studies are also necessary on social systems, ethnic structures, political and power structures, interest in group formation, land tenure systems, attachments to land, rights and privileges, attitudes to modernisation, motivation for achievement and types of participation. Only an organized interdisciplinary approach has promise of effectively meeting this challenging need. An essential need is to develop a sound organisational structure capable of comprehensive planning and coordination of policies and activities necessary for the protection of catchments and the integrated development of natural resources.

3.1 National Watershed Commissions

The formation of a Watershed Commission or Authority at the national level has helped governments to obtain an overall view of a country's needs and to voice these needs in an authoritative manner. Such commissions can draw up policies and plans so as to achieve an overall, conservation-oriented development of land and its related resources in a balanced coordinated manner. Such organizations must be vested with powers and responsibilities for comprehensive planning and efficient execution of works and must cut across disciplinary and agency boundaries. There should be representation of the various interests and disciplines concerned, such as forestry, agriculture, soil conservation, hydrology, economics and rural sociology. They should be headed by a person of high calibre with administrative experience. They should have a professional staff of conservationists, soil scientists, engineers, agronomists, agrostologists, hydrologists, foresters, sociologists and economists. Since such trained and experienced staff is generally not available in developing countries, specialized training of personnel is a vital part of the creation of this kind of authority.

The commission also must act as apex body in respect to various subordinate authorities and disciplines connected with management of water and related land resources, and provide information, advice and guidance to the subordinate bodies. Another responsibility of such organization would be to assemble, analyse and distribute information.

A river system from source to sea is one organic whole and any intervention in one section of it will affect its entire regime; therefore a watershed or basin may be viewed as a unit of organization and planning. Tributary and sub-watersheds (or sub-basins) could form sub-units for micro-planning and control. Thus, under the national commission or authority there may be subordinate agencies, such as river basin boards or regional watershed authorities ("catchment boards").

3.2 River Basin Boards

River basin boards or authorities need to be established for each major river system or, in the case of very large or international rivers, for parts of a river system. These boards would act as subordinate agencies of the National Organisation and would be responsible for identification of the problems, surveys, coordinated planning and execution of works. Various disciplines, social and political groups and local authorities would be represented in them. They would be supported by professional staff. Such boards would be responsible for maintaining coordination between local administrations, technical staffs and cooperating agencies. The boards would develop soil survey and soil erosion criteria and make specific recommendations on alternatives for land treatment within their watersheds. Local or regional watershed boards which are established under higher authorities could also be useful in decentralizing control of large river basins.

Figure 2. Typical terracing for conservation on the steep slopes in the foothills on the Himalayas (FAO photo by I.A. Simpson, India, 1962.)

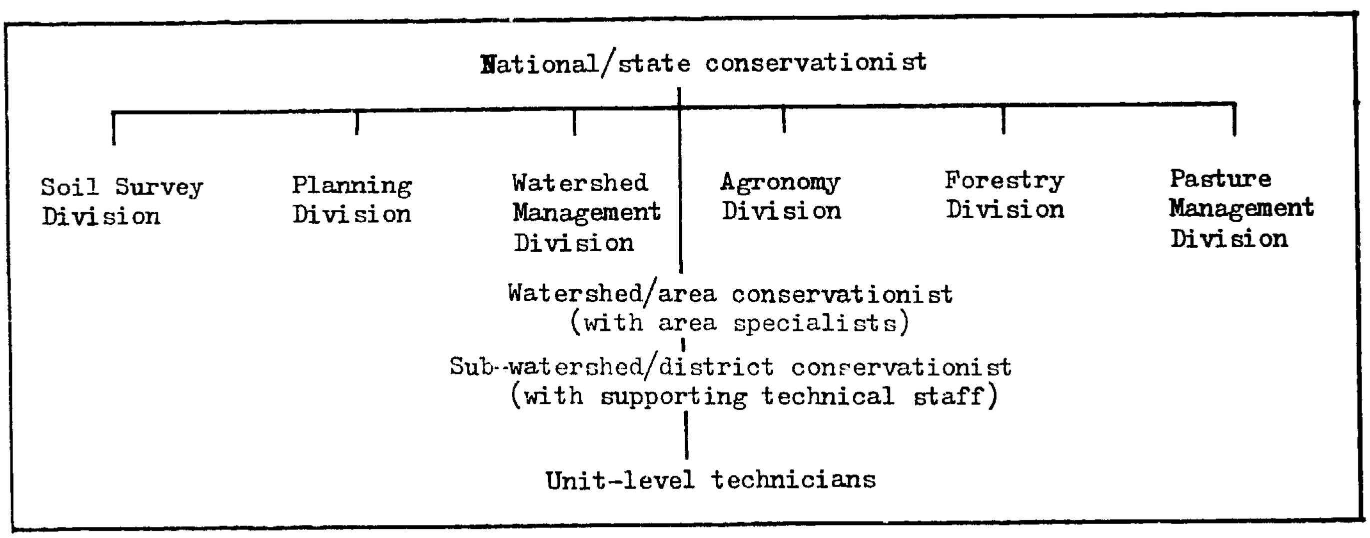
The boards might also have to organize demonstration centres for local administrations and the public where land-use adjustment, improved woodland and grassland management, soil conservation, land grading, water control structures, water management, and better farming techniques would be shown and taught. The centres could serve as focal points for the growth of better practices and could provide the results of research under actual field conditions. Another of their functions would be the training of large numbers of technical personnel under field conditions - which is to say the creation of a cadre capable of commanding the respect of land owners and land users.

3.3 A Soil Conservation or Watershed Management Service

A dedicated service of individuals who are technically qualified to handle watershed problems, backed by strong administration and have the confidence of the public is essential to a country's watershed management capability. Within the watershed area, the forest services should retain responsibility for the conservation, management and development of forest reserves and national forests. However, the planning of all soil conservation and management activities on other wild lands, farm lands, and range lands, should be the responsibility of a special soil conservation and watershed management service. This new organization should have the professional capability for investigating, planning and executing all soil and water conservation activities according to the guidelines and technical standards provided by the River Boards.

It is important that the Soil conservation organization cooperates with the forest service and that it develops cooperative programmes with private and public agencies, universities and research laboratories. It should operate demonstration projects initiated by the River Board authorities and provide leadership in integrated watershed management. A suggested organizational framework is given in Table 1.

Table 1 - Possible organization for a watershed management organization



3.4 Financial and Technical Assistance

The degree and degradation of the world's river basins calls not only for wide awareness, but also for a coordinated application of both technical development and resources. It is to be recognized that investments in soil and water conservation or in long term forest development projects may not be able to compete with other claims on the financial resources of a developing country, where every cent of investment is expected to bring quick benefits. When it is beyond the economic and technical resources of the local communities of a developing country, then ungrudging aid from the developed countries and the international community is called for in terms of financial aid, guidance, planning, equipment, training and demonstration so as to develop watershed management capabilities which will cope with the problems of that country.

4. PUBLIC COOPERATION AND PARTICIPATION

The success of any watershed management programme does not rest solely on scientific, technical or economic considerations. It also involves social and political factors. It is necessary to understand the social traditions and attitudes of the people and win their hearts and confidence. Human motivation and public cooperation are essential tools to achieve success in proper land use management.

Since land use adjustment is the key phase of the overall watershed programme, really effective management can be achieved only when land owners themselves take active part in the work. Watershed management organizations should aim at developing local capabilities for the formulation and execution of their programmes by organizing provincial, district and local organizations of soil and water conservation with local leadership.

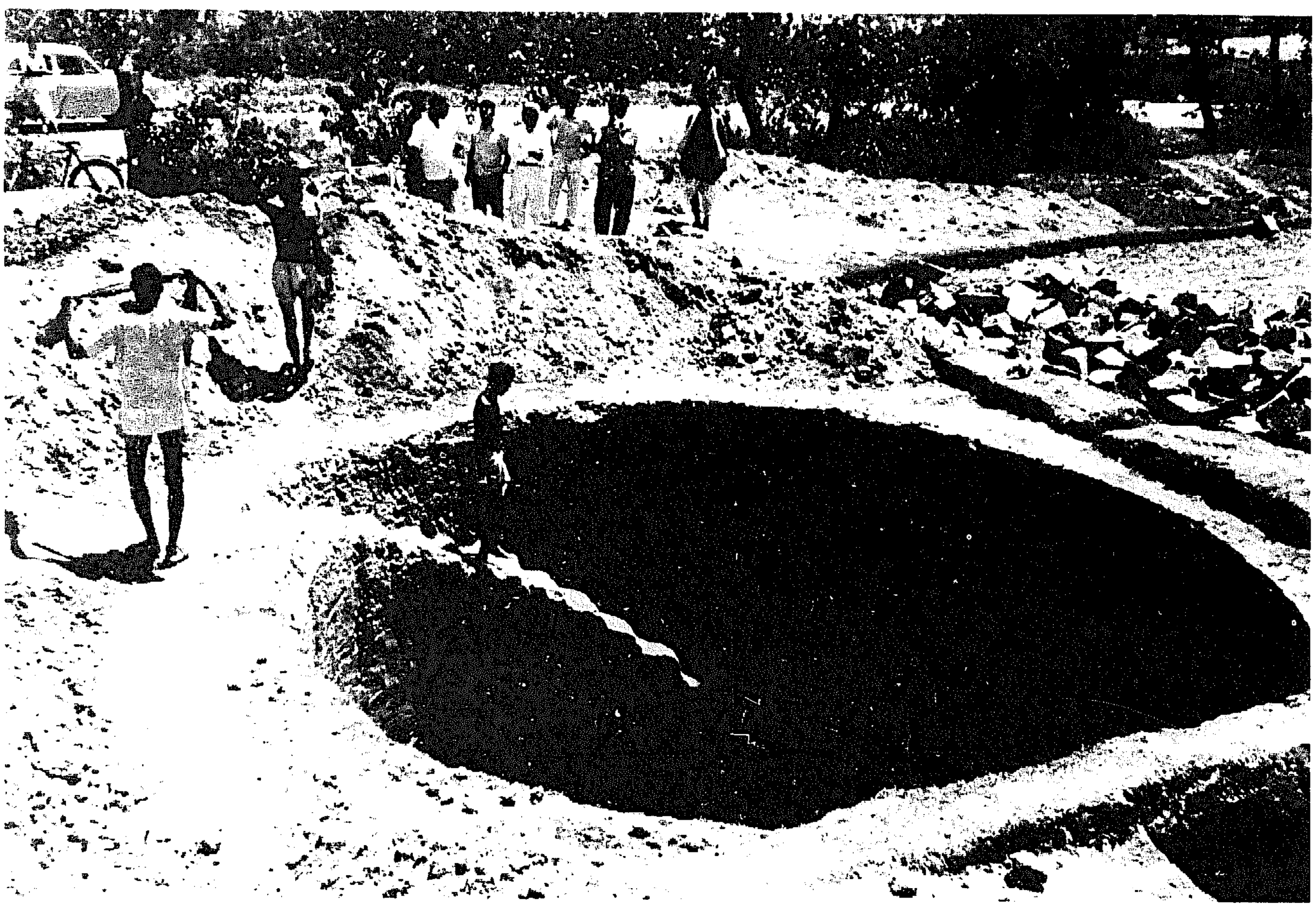


Figure 3. Local efforts. A new 10-metre open percolation well under construction in India built through WFP/FAO labour-intensive, local efforts (World Food Programme/FAO photo by Peyton Johnson, India, 1970).

5. INFORMATION AND EDUCATION

Every citizen should have the opportunity to develop an awareness and appreciation of his country's natural resources. He should know how they affect his life, how to use and how to safeguard these resources for economic and political organizations. Natural resource conservation should form an essential part of school curricula. Textbooks and education courses should be developed, explaining in simple language the principles and benefits of integrated resource management. Hill people may be trained in forestry skills. Farmers' information and training camps and tours can provide simple instructions in soil and water conservation and proper land use. The press, radio, films, television, bulletins, exhibitions and demonstrations should be used for this purpose. Seminars on soil and water conservation can be useful.

6. INCENTIVES

Sometimes financial and social incentives are necessary to develop human motivation. For example, the inhabitants of watershed areas can create and plant forest plantations and help protect the forests. One way to achieve this is to give them a share in the proceeds from the sales of forest products. Granting permanent rights to land users when they adopt soil conservation practices can be an effective incentive. Creation of forest-based industrial cooperatives of the local population, with local leadership, can provide motivation and develop a desire for active participation in the development of forests. Young men from tribal groups and forest dwellings, for example, may be educated and trained and given employment in forest and soil conservation organizations and extension work.

7. SUMMARY REMARK

What is particularly important in putting any of these ideas and reforms into effect is the consciousness that new ideas are more acceptable to people when they come not from outsiders but from their own kind of people and especially those with whom they grow up and trust. People are the most important factor in good watershed management and resource development.

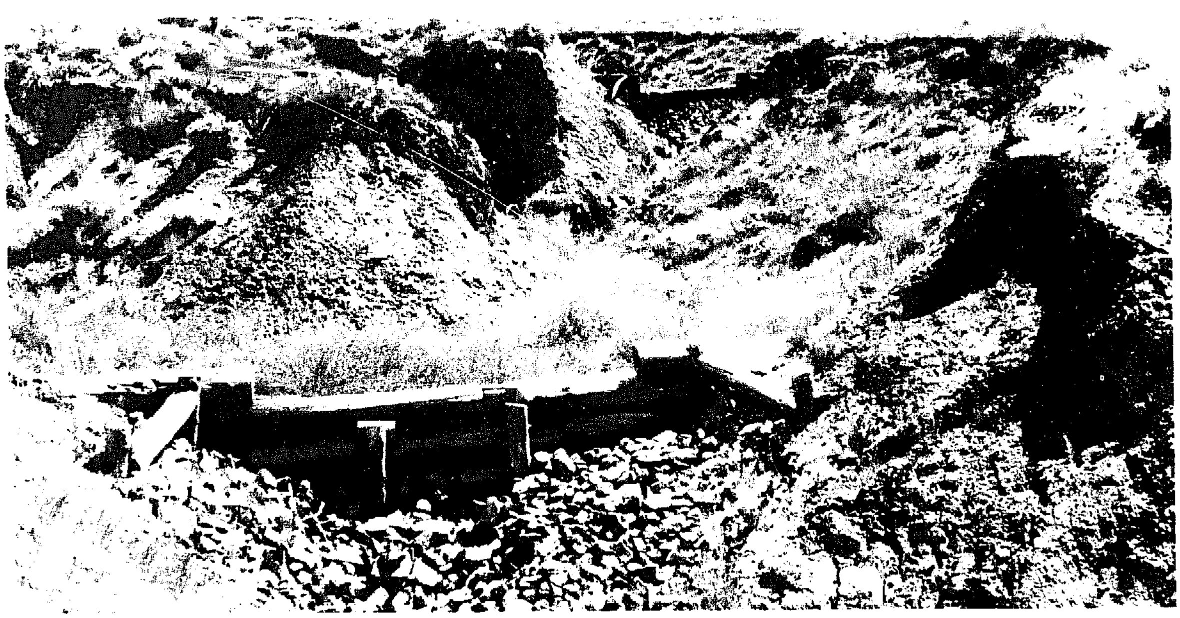


Figure 4. Conservation measures often may rely on local materials and hand labour, for example, in gully correction work with small logs and rocks (Photo courtesy of U.S. Forest Service).

XVI.

FOREST MANAGEMENT TO MINIMIZE LANDSLIDE RISK

by
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1. INTRODUCTION

1.1 Magnitude of Landslide Erosion

Mass wasting is the dominant erosional process in most steep-sloped catchments. And the major mechanism in this process is the landslide (2, 6, 8, 19, 24, 25, 29). In this paper, unless explicitly stated to the contrary, the term "landslide" will be used in reference to debris avalanches and other forms of shallow failures.

One of the consequences of landslides is the increase in sedimentation estimated as accounting for 25 percent of sediment load of the Eel and Mad River Basins (26), but may be as high as 50 percent. Why the uncertainty? The principal obstacle to the study of landslides is that, although the amount of material eroded may be large, storms that produce landslides occur only infrequently - in the order of only once every 6 or more years. A short-term experiment, therefore, is unlikely to measure landslide erosion together with other types of erosion. Typically, a landslide-producing storm imposes itself upon another experiment. And the investigator measures its effect in this experiment. The data from such studies demonstrate that landslides can produce substantial amounts of erosion. After a large storm, Dyrness (6) found about 0.75 landslides per km^2 in a 61 km^2 drainage in Oregon. That represented erosion rate of about 1 000 metric tons per km^2. As high as that rate may have been, the rate was five times greater in a 101-ha experimental basin within the drainage, which had 24.7 ha of recent small clearcuts and 6.3 ha of roads (7).

1.2 Types of Landslides

Each of the various types of landslides is influenced to some degree by vegetation manipulation (27). Shallow slides, such as debris avalanches, however, are the ones most likely to be triggered by logging or destruction of the forest cover. They are the ones over which the forest manager can exert the most control (29). Less subject to control are deep-seated failures. Roads or tractor trails built for timber harvesting can trigger such failures when improperly placed on unstable terrain.

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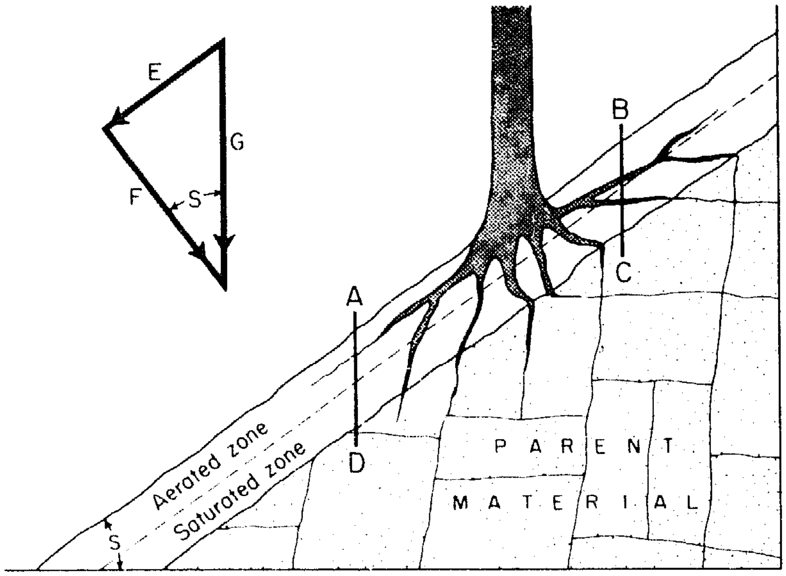

Fig. 1. Stability of a slope is determined by slope angle, geology and moisture conditions. The slope angle (S) determines the partitioning of the force of gravity (G) into a downslope component (E) that promotes failure and a component (F) that promotes stability

Fig. 2. Landslides often occur at the head of drainageways. These took place on a clearcut block in the Klamath Mountains, California.

1.3 Factors Related to Occurrence of Landslides

The factors that affect soil holding a single tree on a steep slope are many (Fig. 1). The slope angle S determines the partitioning of the force of gravity G into a downslope component E that promotes failure and a normal component F that promotes stability (through its effect on the frictional resistance to sliding along CD). The resistance to sliding at CD is governed by the soil, geology, and moisture conditions at that surface. If the potential failure is at the interface between the soil and parent material, the gross roughness due to stratigraphy or jointing of the parent material surface will also affect frictional resistance.

Cohesion of the soil tends to prevent movement. Generally, cohesion increases as the soils become more finely textured. Counteracting this tendency the cohesion of fine textured soils is greatly reduced as the soil moisture increases. Soil saturation will also, by creation of high pore water pressures, "float" the potential failure block (ABCD) on the surface (CD). If this zone of saturation is confined below an impermeable stratum, such as a B horizon, very high pore water pressure can result. The tree growing on ABCD promotes stability in two ways. It decreases soil water by transpiration, and its roots mechanically tie the potential failure block ABCD to stable portions of the slope. The lateral anchoring to the sides and upslope ABCD probably adds more to stability than roots tying it to the parent material beneath. It is principally this connection between slope stability and tree roots that associates landslide occurrence to root decay following logging.

Slope is probably the key factor related to the occurrence of landslides. Slides can only occur when slopes are steep enough for some other factors to combine and produce a stress that exceeds the resistance of the soil or rock material making up the slope.

Other factors related to the occurrence of landslides are physiography, soil and geology, climate, vegetation, and disturbances. Since some disturbance is an inevitable part of forest management activities, it is usually safe to assume that they will increase landslide risk.

2. APPRAISAL OF LANDSLIDE RISKS

2.1 Physiography

2.1.1 Slope

Analyses on granitic terrane have shown that slope "explained" from 44 to 77 percent of the influence of site on the occurrence of landslides (21). Mudflows have been reported on slopes as flat as 3° (4) and debris avalanches have occurred on slopes as steep as 60° (25). Slopes between 30° and 40° seem to be the most frequent sites for landslides. Neglecting the effect of stratigraphy, for the moment, the slope at which landslides occur increases as soil texture becomes coarser. Therefore, the critical slope (the slope above which nearly all landslides occur) is much steeper on granitic terrane which typically has a coarse textured soil than where the parent material is basalt, which typically developes a finely textured soil.

2.1.2 Position in relation to drainages

Since excess moisture is almost always associated with landslides, most failures occur in drainages or adjacent to stream channels. A variable indicating whether the contours were convex or concave (in plan view) accounted for about 20 percent of the variability of occurrence of landslides (21). In profile, the most frequent site for landslides seems to be just below a convex break in slope at the head of a small drainage (Fig. 2). This coincidence of landslides and drainage pattern indicates that the subsurface drainage is generally parallel to surface drainage, but there is evidence to suggest that this is not necessarily the case. In site appraisal, consideration should be given to the areas where it is expected that subsurface water will concentrate rather than relying solely on surface contours.

Landslides frequently occur adjacent to flowing streams, where - besides excess subsurface canyon bottom water - slopes may be undercut by stream action. Undercutting removes the mechanical support for the slope much in the same way that a road cut might trigger a landslide. Usually, failures of this type will be found on the outside of bends in the stream (Fig. 3).

2.1.3 Unstable areas

An area with a history of landslides is likely to have recurrences of these phenomena. In southern California, 81 percent of the area of debris slides occurred in locations with previous slide history (14). Such landslide-prone areas can be detected on the ground or on aerial photos by the presence of uneroded landslide scars, longitudinal flow ridges, landslide deposits, landslide toes intruding on to stream channels, or bowl-shaped depressions.

2.2 Soil and Geology

2.2.1 Rock type

Rock type affects the rate of weathering and the type of soil that develops. In the Cascade Mountains of central Oregon, for example, landslides associated with roads occurred 27 times more often on green tuffs and breccias than they did on other geologic parent materials (6). Since geology and soil interact with climate and vegetation, it is difficult to accurately judge the effect of rock type on landslides apart from the other factors. A rough approximation can be obtained by combining results of different studies (Table 1). These data, while incomplete, illustrate the interaction between geology, topography, and roads. Presumably, a similar relationship exists with respect to timber harvest. As expected, the largest sediment production was related to roads constructed on the steepest slopes and on a granitic parent material. At the other extreme, no measurable increase in road erosion was found on glaciated metamorphics and basalts of gentle slope. Roads on granite of moderate slope produced little sediment, but they produced substantial amounts on sandstone, which was also a substantial sediment producer in an undisturbed state.

2.2.2 Weathering

Most parent materials are not susceptible to landslides in an unweathered condition. As weathering increases, landslide susceptibility increases, with thickening of the soil mantle and fracturing of the parent material. Intermediate in the weathering process, maximum vulnerability is achieved when the mantle is fairly deep and the soil is still not cohesive. As weathering proceeds, the formation of clay and soil aggregation leads to a decline in susceptibility to landslides. On steep slopes, the process is often arrested at early weathering stages owing to continual surface erosion and landsliding.

2.2.3 Stratigraphy and structure

Slopes that are nearly parallel to bedding planes of sedimentary parent materials, or to the direction of jointing and fracturing of any parent material, are more susceptible to landslides than those which are not. The reason for this difference is most easily illustrated in a sedimentary parent material.

In the parallel situation, stratigraphy promotes landslides in two ways. First, the surface of the parent material and interfaces between strata in the parent material provide zones of weakness and ready-made failure surfaces (Fig. 4). Second, the beds will tend to concentrate and return percolating subsurface water to the surface. Abundant water there may produce high pore-water pressures and increase susceptibility to landslides. In the opposite situation, the geologic strata are more or less normal to the surface slope (Fig. 5).

Fig. 3. Landslides often take place next to flowing streams. This landslide was started by undercutting of banks of the Mad River, in northern California.

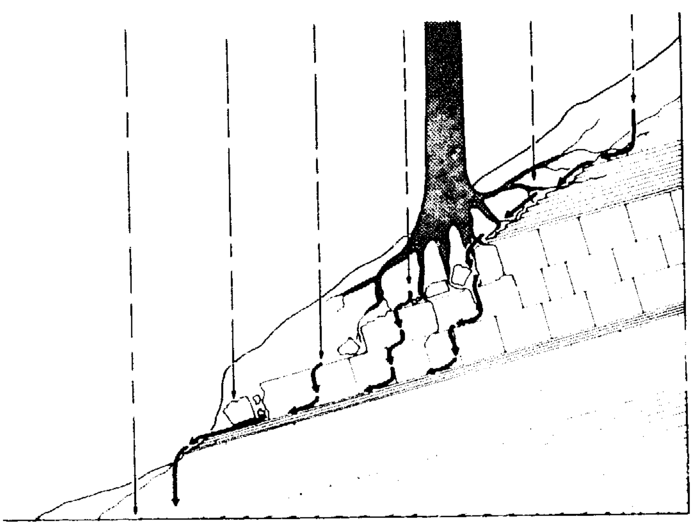

Fig. 4. Subsurface rainwater flows in the direction of the slope when geologic strata dip toward slope.

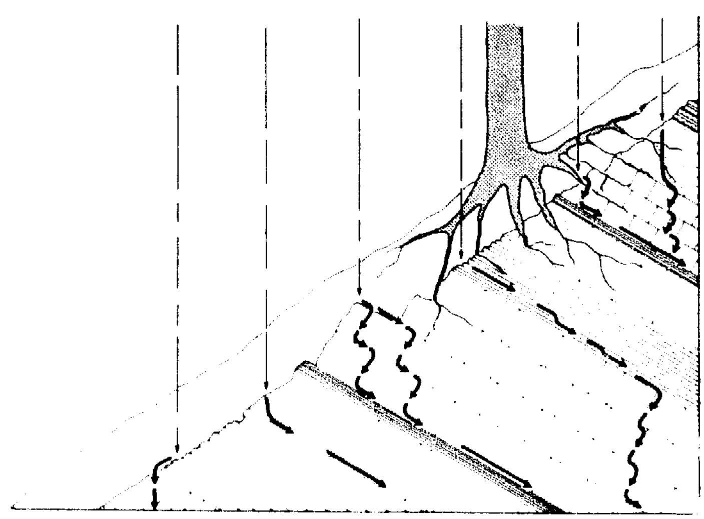

Fig. 5. When geologic strata dip away from the slope, subsurface rainwater flows in that direction.

Table 1. Erosion and Sedimentation from Logging Roads in the Western United States, by Location, Soil, Slope, Vegetation Type

Location	Soil parent material	Slope	Type of vegetation	Sedimentation on Deposition	Years Sampled	Average amount of material removed for the period: Undisturbed	Average amount of material removed for the period: Disturbed	Ratio Disturbed/ Undisturbed	Reference
		Pct.				Metric tons/sq. km./yr.			
Idaho	Granite	70	Pinus ponderosa	Deposition in dams in small ephemeral drainages	6	8.8	396	45.2	(16)
Oregon	Sandstone	20-50	Psuedotsuga menziesii	Suspended sediment from watersheds	1	Approx. 42	94	2.2	(5)
Colorado	Glaciated Metamorphics	30-40	Pinus contorta Abie lasiocarpa	Deposition in dams in perennial drainages	10-14	1/ 2.2	(2/)	0.0	(15)
Idaho	Granite	35-55	Pinus ponderosa	Deposition in sediment dams in ephemeral and perennial stream	4-5	0.0	1.2	--	(10)
Oregon	Glaciated basalts	20-30	Psuedotsuga menziesii	Suspended sediment at gaging station	4	Average <10 ppm	(3/)	--	(4/)
Oregon	Tuffs and breccias	55	Psuedotsuga menziesii	Suspended sediment and bedloads from watersheds	2	25.6	56	2.2	(7)

Source: (22)
1/Assumed sediment volume weight of 70 pounds per cubic foot
2/Slight increases traced to roads but not significant
3/No change except slight increase during road construction
4/Unpublished data on file at Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon.

Because weaknesses in the bedding planes of the geologic formation are normal to the direction of failure, they contribute little to failures. Such slopes are also more stable because the strata tend to direct water away from the surface rather than concentrating it there.

2.3 Climate

Climate determines the type of storm that will be required to trigger a landslide. In humid climates, the soil mantle may be in a barely stable condition throughout much of the year. In such situations, only a relatively short period of above-normal rainfall is necessary to trigger failures. For example, diurnal rainfall of 50 mm was sufficient to release earthslides in the Torentrask-Narvik area of northern Norway and Sweden (19). At the other extreme, in southern California, Bailey (1) places a rainfall threshold at about 460 mm in 12 days on coarse-textured soils that were rarely above field capacity. The storm in Norway would occur about once every 6 years; the storms in California, once every 8 years.

Just what is the critical climatic event will depend on two factors: the rainfall regime, and how rapidly moisture can drain from the soil. The more slowly moisture can drain from the soil, the more susceptible slopes will be because they will carry over from storm to storm. Except for permafrost environment the temperature regime has little to do with the relative importance of landslides as an erosional process. Landslides can be as important an erosional process in a sub-arctic environment (19) as in tropical areas (24).

2.4 Vegetation

Although vegetation may increase susceptibility to landslides (25), most evidence suggests that the more vegetation on a site the lower is its susceptibility to landslides. An example of this condition, although not in a forest type, shows landslide occurrence inversely correlated with size and density of vegetation (Table 2) (3). The only deviation from that trend was in the riparian zone; where, in spite of heavy vegetation, the disturbing influence of the stream caused more landslides than in other less dense parts of the chaparral. Another exception to this inverse correlation between landslides and vegetation was found in a freshly burned area (Table 3), which had only 62 percent of the landslide erosion measured in the area that had not burned for 49 years. Apparently, a freshly burned area is spared some landslide erosion because low infiltration rates prevent sufficient water from entering the soil to trigger landslides. At the same time, soil in such an area is fully supported by the roots of the former vegetation.

Table 2: Percent of Area of Vegetation Types that Slipped on the Bell Canyon Watershed, San Dimas Experimental Forest, California (1966-1967) 1/

Vegetation Type	Area in Slips
Sage and barren	23.9
Perennial grass	11.9
Annual grass	6.5
Riparian woodland	5.3
Chamise chaparral	3.3
Oak chaparral	2.6
Broadleaf chaparral	1.2

Source: (3)

1/ Average slope of study areas ranged from 55 to 59 percent

Table 3: Effect of Fire and Type Conversion on Landslides during 1969 Storms, San Gabriel Mountains, California 1/

Vegetative Cover	Year Burned	Landslides m^3/ha
Grass 2/	1960	844
Chaparral	1960	298
Chaparral	1919	16
Chaparral	1968	10

Source: (20)

1/ Average slope of study areas ranged from 55 to 59 percent
2/ Converted after fire

Within a given size of plants, species may be an indicator of the likelihood of landsliding. Bailey (2) has found that Populus tremuloidies was an indicator of instability. This species favoured wet sites and could propagate itself by layering if its roots were torn by movement. These two characteristics gave it a competitive advantage over other species and caused it to dominate areas which were creeping or susceptible to landslides.

Pioneer species of all types may indicate landslides since they would be the first to invade landslide scars or deposits. Creep often precedes landslide failures, therefore, tilted trees may indicate prior movement - especially if the tilts are in differing directions.

One common landslide indicator - but of doubtful value - is curved tree trunks. In the deciduous forests of the eastern United States, no evidence has yet been found to substantiate the contention that curved tree trunks indicates soil creep (18). A curved tree trunk could indicate soil creep, a landslide, or the potential for a landslide, but on steep slopes most of the forces against the trunk are downslope.

3. EFFECT OF CUTTING TREES

3.1 Changes in Evapotranspiration

A mature forest depletes soil moisture at a near maximum rate. After a timber harvest, therefore, the soil moisture regime will be greatly altered. During most of the year, soil on cutover lands will have higher moisture content than that on forested lands (Fig. 6). Generally, the drier the climate, the more important will be the role played by differences in soil moisture depletion between forested and cutover lands. If both a forested and a clearcut area are near field capacity during most of the year, the effect of the timber harvest may be negligible.

As far as landslides are concerned, it is the amount and duration of the deficit which are important. If the period of deficit does not extend into the portion of the rainy season when landslide producing storms are most likely to occur (Fig. 7), then differences in soil moisture may be of little practical consequence. If deficit period coincides with the period of maximum landslide stress (Fig. 8), then the soil moisture depletion effect of the timber harvest may be crucial and lead to substantially more landslides in a clearcut area. As regrowth occurs, the soil moisture depletion effect

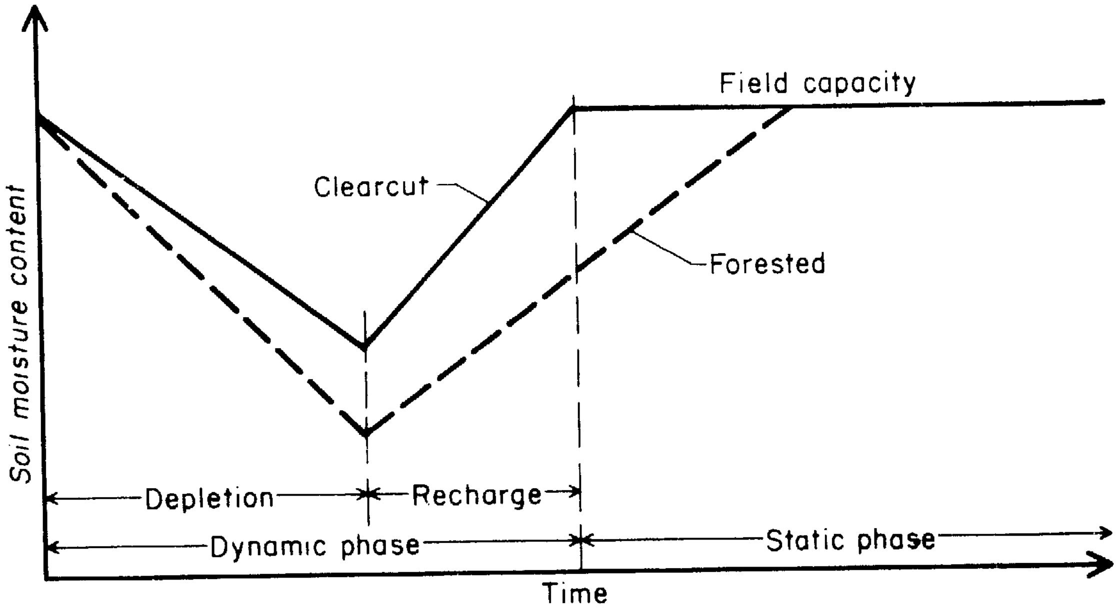

Fig. 6. Idealized representation of soil moisture cycle in forested and clearcut areas. (9)

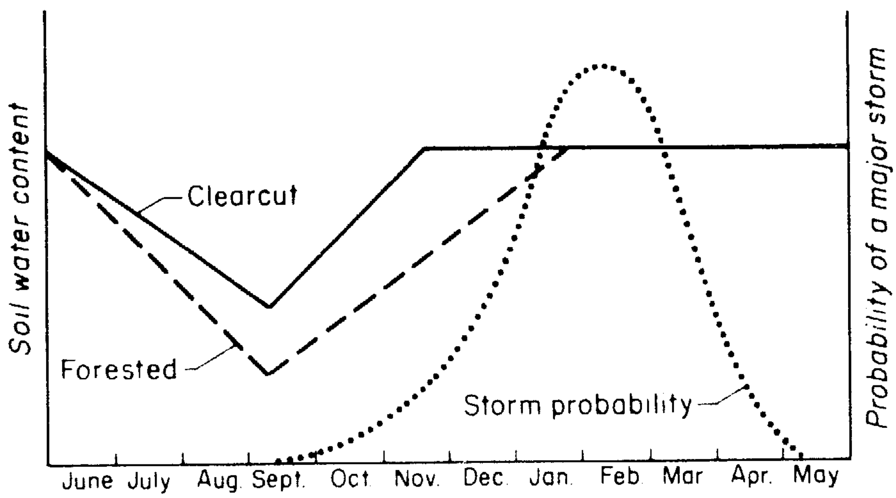

Fig. 7. Idealized soil moisture deficit which does not coincide with period of landslide producing storms.

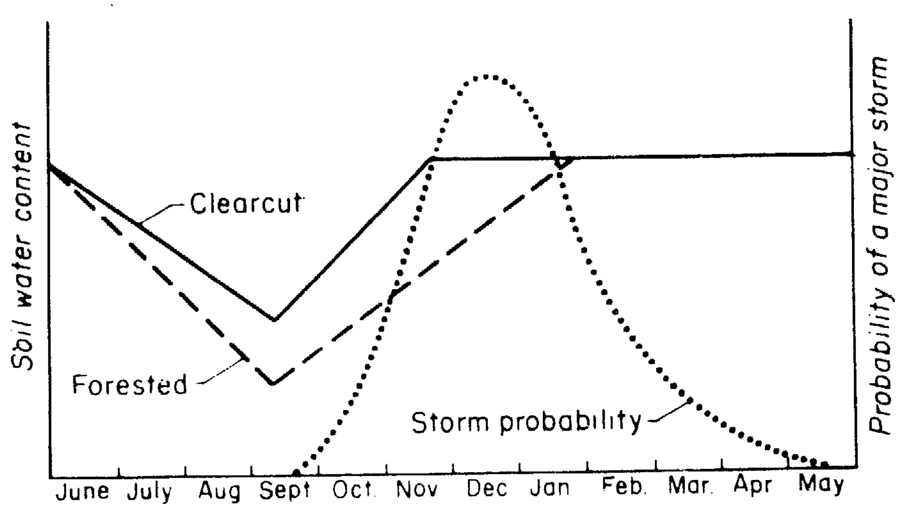

Fig. 8. Idealized soil moisture deficit which coincides with landslide producing storms.

diminishes. Its duration will depend upon the vigour and density of the vegetation that follows the timber harvest.

3.2 Root Decay

Under most circumstances, most of the increase in landslides after timber harvest can be attributed to decrease in the strength of the slope resulting from root decay. Kitamura and Namba (12, 13) indexed the contribution of tree roots to slope strength by the force required to uproot stumps and trees. The force required to uproot a stump declined rapidly after harvest, but there were species differences - presumably related to decay resistance of the roots (Fig. 9). Cryptomeria japonica was the best for the prevention of landslides; Larix leptolepsis was intermediate, and Pinus thunbergii was the least effective species.

3.3 Regrowth of Vegetation

3.3.1 Seedlings

The uprooting resistance of seedlings and young trees that develop after a timber harvest vary only slightly among species - especially in the early years (Fig. 9) (12, 13). This finding seems reasonable since the mechanical differences between species would not become apparent until root systems were nearly completely developed and substantial amounts of heartwood had been created.

3.3.2 Sprouts

In a sprouting species, it seems likely that the pattern just described would be altered. In addition to a decline in strength from the stumps which die after harvest and an increase in strength from seedling reproduction, there would be added a strength regime of stumps which coppiced. These stumps presumably would enter into a brief period of decline while the root systems atrophied in response to the cutting. A period of rapid recovery of strength would follow as sprouts develop. Just how much effect sprouting might have on total slope strength would depend on the proportion of stumps which sprouted.

3.4 Net Slope Strength

Uprooting resistance does not necessarily equal the contribution of roots to slope strength, but presumably the two are closely correlated. To estimate the net trend of slope strength by adding resistance curves from both stumps and reproduction would probably be an oversimplification. Nonetheless, it would be instructive to do so because it highlights even more markedly the differences in slope strength due to differing species and cutting systems (Fig. 10).

Whether the greater vulnerability of one species over another is of practical importance depends upon where a critical resistance threshold appears on the ordinate. If landslides are very unlikely unless the net uprooting resistance drops below two, then the difference between species would be of little importance. If, on the other hand, the critical value were four we would find for example, that P. thunbergii was vulnerable to landsliding after harvest but C. japonica was not (Fig. 10). If the threshold were at six, both species would have a period of vulnerability but that of C. japonica would be shorter. Storms that can produce stresses equal to the lower resistance values are more frequent than those that can overcome the higher resistance values. This phenomenon tends to accentuate the importance of differences among tree species (Fig. 10).

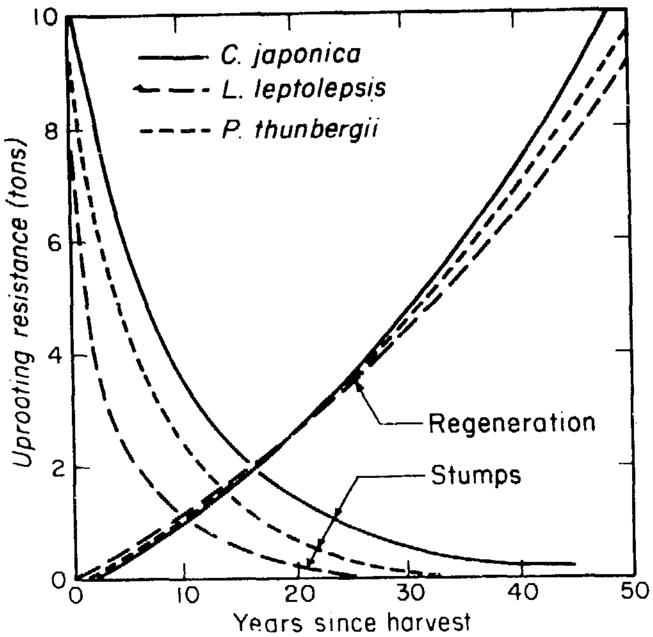

Fig. 9. Inferred forest contribution to slope strength related to species and time since harvest. (17)

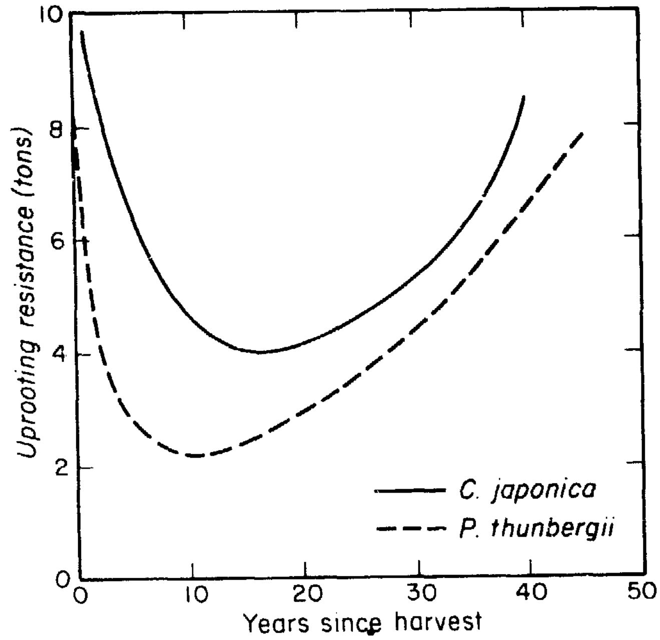

Fig. 10. Inferred net strength of slopes supporting different tree species.

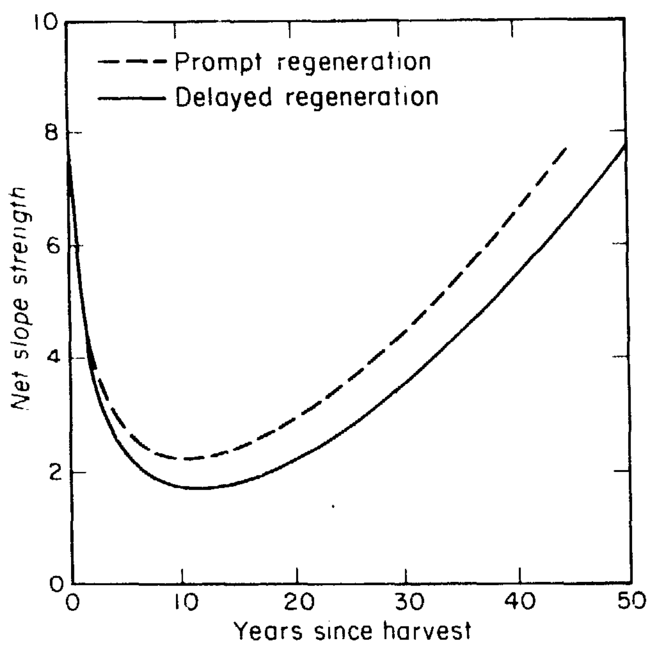

Fig. 11. Inferred effect of a 5-year delay in regenerating a Pinus thunbergii clearcut.

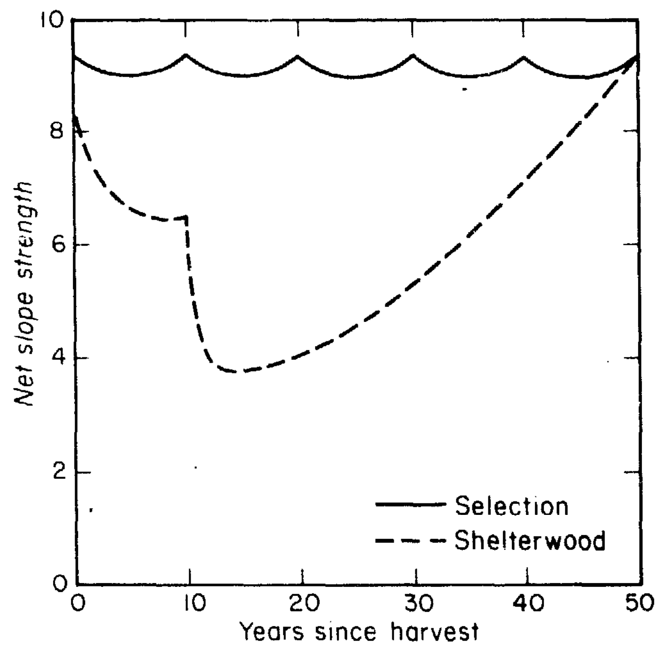

Fig. 12. Hypothetical trends in slope strength under shelterwood management and selection management.

4. EFFECT OF SILVICULTURE SYSTEM

4.1 Clearcutting

As far as landslides are concerned, clearcutting is the least desirable silvicultural system because strength is reduced simultaneously over the whole harvest area. In an extensive inventory covering over 12 000 km^2 in Japan, more than 10 000 individual landslides were tallied. The volume of soil moved was nearly 2.5 times greater on the areas supporting even-aged plantations than it was on areas supporting natural forests or mixed forests (17). These findings support the admonition that even-aged, single-species management should be avoided on potentially unstable slopes.

Another reason for avoiding clearcutting where landslide risk exists is the effect on slope strength of any delay in achieving prompt regeneration. A 5-year delay in securing regeneration P. thunbergii illustrates this point (Fig. 11). Not only is the period of vulnerability extended but also the minimum strength is reduced.

4.2 Shelterwood System

Landslide risks resulting from even-aged management can be reduced by turning from a clearcutting system to a shelterwood system. Hypothetical curves show net slope strength when the first harvest of a non-sprouting species removes a volume equivalent to half of the forest's contribution to slope strength and second cutting, 10-years later, removes the remaining volume (Fig. 12). This cutting system achieves two desirable objectives: (a) increasing the minimum strength, and (b) reducing the duration of vulnerability for any resistance threshold.

4.3 Selection System

If we assume five evenly spaced cuts over the rotation age of the forest, we find that a selection system will weaken in slope strength only slightly (Fig. 12). Clearly it is the best system for potentially unstable areas if there are no other adverse considerations. If a selection system required the use of tractors for yarding, it could have greater adverse effect on slope stability than could even-aged management with yarding accomplished by cable systems.

4.4 Coppice Management

With any silvicultural system, a species which will sprout can probably maintain slope strength at a high enough level so that the removal of trees during the harvest will cause only a trivial increase in landslide risk. This would be true only if management of the stand is prudent and maintains high levels of growing stock. In the inventory study in Japan (17), among the various forest conditions, the most landslides were found in the "poor coppice forest."

5. EFFECT OF OTHER FOREST MANAGEMENT ACTIVITIES

5.1 Roads

In most circumstances, roads more frequently cause landslides than do timber harvests. Roads gouge deeply into subsoil and parent material; logging disturbance is generally restricted to the soil surface. Road cuts can remove downslope support that was buttressing potentially unstable areas. Roadfill material may be deposited on slopes barely strong enough to support the weight of the existing mantle. Roadcuts intercept subsurface water and may channel it to areas which are unable to cope with the additional flow. For these reasons we find frequent references to the importance of roads.

During the 1964-65 floods, 72 percent of the landslides on an experimental forest in Oregon were associated with roads (6) - although roads occupied only 1.8 percent of the area. This intensity of landsliding was 315 times greater than that found in undisturbed portions of the experimental forest. Landsliding in the logged portion was only 10 times greater than undisturbed conditions.

Similar results have been reported for forests elsewhere. Roads were involved in 60 percent of the damage to National Forests of Washington and Oregon after the 1964-1965 floods (23). In southern Idaho, 90 percent of the failures studied were associated with roads (11). In Oregon, a single road failure produced 40 percent of the total sediment yield for the year from a 303-ha drainage containing 4 km of roads constructed to permit clearcut logging of about 25 percent of the watershed (5). In all these cases roads had been constructed on steep slopes.

One of the most important ways that forest management can minimize landslide risk is to minimize road mileage and to the fullest extent possible, locate necessary roads on the more stable portions of the landscape.

5.2 Fire

The likely immediate effect of a fire is to reduce landslide risk (Table 3). As time passes, however, the roots of the former vegetation decay, and new vegetation restores infiltration. A burned area then becomes much more vulnerable to landsliding (Table 3). In total, the effect of a fire on landslide occurrence is quite like that of a clearcut timber harvest.

5.3 Conversion

The conversion of an area from woody vegetation to grass is the most hazardous vegetative manipulation that managers can undertake. If the terrain has an appreciable slope, it is safe to assume that some portion of its stability was due to the stabilizing effect of the roots of the woody vegetation. Consequently, increased erosion and increased landsliding are often associated with conversion (9, 21, 28). Conversions are especially hazardous because the herbaceous vegetation promotes rapid infiltration without lending appreciable mechanical support to the slope that was formerly dependent upon it. A conversion is like a clearcut with no regeneration (Fig. 9).

6. PREPARING MANAGEMENT PRESCRIPTIONS

6.1 Critical Slopes

In analysing landslide problems associated with a timber harvest, first prepare a slope map of the harvest area. Next, determine what is the lowest slope upon which landslides have occurred in the past. Group all slopes flatter than its lowest one into a single slope class that presumably presents no landslide risk. In actuality, some landslides will occur in this area. Because smoothing necessarily accompanies the mapping process, small steep facets will be incorporated in areas that have much flatter slope on maps. In a 1969 study (21), 2 percent of the landslides occurred in areas mapped as having slopes less than 28° - even though all slides measured were on slopes steeper than 31°.

If there are sufficient data about slopes on which landslides have been occurring, another slope class could be created. This class would include all areas steeper than those which experienced landslides. Normally, such areas will be found to be rock outcrops or to contain a different, more stable geologic formation. If adequate data are not available to define this slope, however, it is better to assume that landslide risk increases with slope. Finally, subdivide the slopes considered susceptible to landsliding into two or more slope classes. The number of classes will depend upon how much of the harvest area is susceptible to landslides and variation in susceptibility. These critical slope classes will then be the focus of further attention in attempts to minimize landslide losses.

6.2 Soil and Stratigraphic Considerations

In areas where soil surveys or intensive geologic mapping has been done, the data compiled can be used to supplement slope information in appraising relative landslide hazard. But before final plans are made, all susceptible areas should be inspected on the ground.

Undoubtedly, circumstances will arise that will make it necessary to cross steep slopes with new roads used for the harvest. If this can be done on soils which are characteristically stable or on areas where the bedding planes are nearly normal to the surface, losses from landslides may be reduced. Even within a geologic formation, there may be subunits exceeding average stability. To the extent that distrubance can be concentrated on those units and reduced on others, the adverse effects of the harvest can be minimized.

6.3 Expected Stress

If data on the types of storms that have led to landsliding are available, they should be used to estimate the recurrence interval of those storms. This information could be useful in predicting the likelihood of a storm during the vulnerable period after a timber harvest. If such information is lacking, a return period between 5 and 10 years should be assumed, using lower values for humid climates and higher ones for more arid climates.

6.4 Potential Losses

6.4.1 Loss of productivity

For each landslide-producing event, between 2 and 6 percent of a harvest area will likely be bared by landslides (6, 7, 21). From data on tree rings, Fujiwara (8) estimated that from 10 to 15 years were required for vegetation to cover landslide scars in Japan. He found that north and east facing slopes recovered almost twice as rapidly as dry south and west slopes.

To appraise the total loss in productivity, the manager should base his estimate on the product of the expected number of landslide-producing storms, the damage expected from each storm, and the loss of growth from the landslide area until they revegetate. In most cases, landslide scars, even after revegetating, will not be as productive as undisturbed soil.

6.4.2 Damage to other values

Related amenities are often as important as the timber resources. Questions to be considered are: Will accelerated landslides from the timber harvest block transportation routes or increase their maintenance costs? Will sediment entering streams damage a valuable fisheries resource? Will wildlife values be damaged? Will the appearance of the area be so degraded as to create political pressures which will inhibit the effective operation of the managing agency?

6.5 Resources Gains from Management

Normally, an area would not be considered for harvest unless it contained valuable wood products. These are usually the most important benefits derived from forest harvesting operations. Other benefits might be the financing of a transportation system needed for other management purposes, the enhancement of wildlife values by creating more open and diverse cover, or increases in streamflow.

6.6 Balancing Gains and Losses

Attempts to appraise the danger of landslides in an area are fraught with uncertainty because of the random nature of storms. This would be true even if the forest manager knew with a high degree of certainty the several parameters that affect landslide risks. His role is to balance potential losses against potential gains. In so doing, he gains a number of benefits. One is a form of self-discipline that helps insure that the desirability of a timber harvest is examined objectively. In such an examination, the ratio of benefits to costs must be considered. Another benefit is that a forest manager who has a firm technological base is in a better position to withstand political pressures that are often brought to bear on management decisions. And he is better equipped to arrive at sound decisions about what can or should be done to minimize landslide risks.

7. REFERENCES

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XVII.

WATTLING AND STAKING

by

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1. INTRODUCTION

Wattling and staking (or "contour wattling") is a watershed treatment chiefly for stabilizing road fill banks and similar areas of bare slopes. It is a combination of mechanical stabilization and re-vegetation which has proved very practical and successful in many parts of the world. The method described here was originally devised in the U.S. Forest Service in the 1930s, although variations of the same general approach are in use in other countries, especially in the Alpine region, where a woven twig style of wattling is well known ("clayonnage"). Because it is labour intensive, it is suited to developing countries where new roads are built in hilly or mountainous regions.

The reader should recognize, of course, that the examples and details in this paper are based on experiences in Jamaica. As with any watershed treatment, the methodology would need adaptation before use in other areas and there are areas where the technique would not be applicable.

2. THE SITE

The wattling and staking treatment is primarily for controlling surface erosion on certain types of fill slopes. The method is not ideal for application on hard cut banks or on areas of mass movement. Even along road fill banks, the following sites are not suitable or should be improved before wattling and staking:

a) cut banks which slide continuously, thus creating danger that the sliding material will cover the staked area below;

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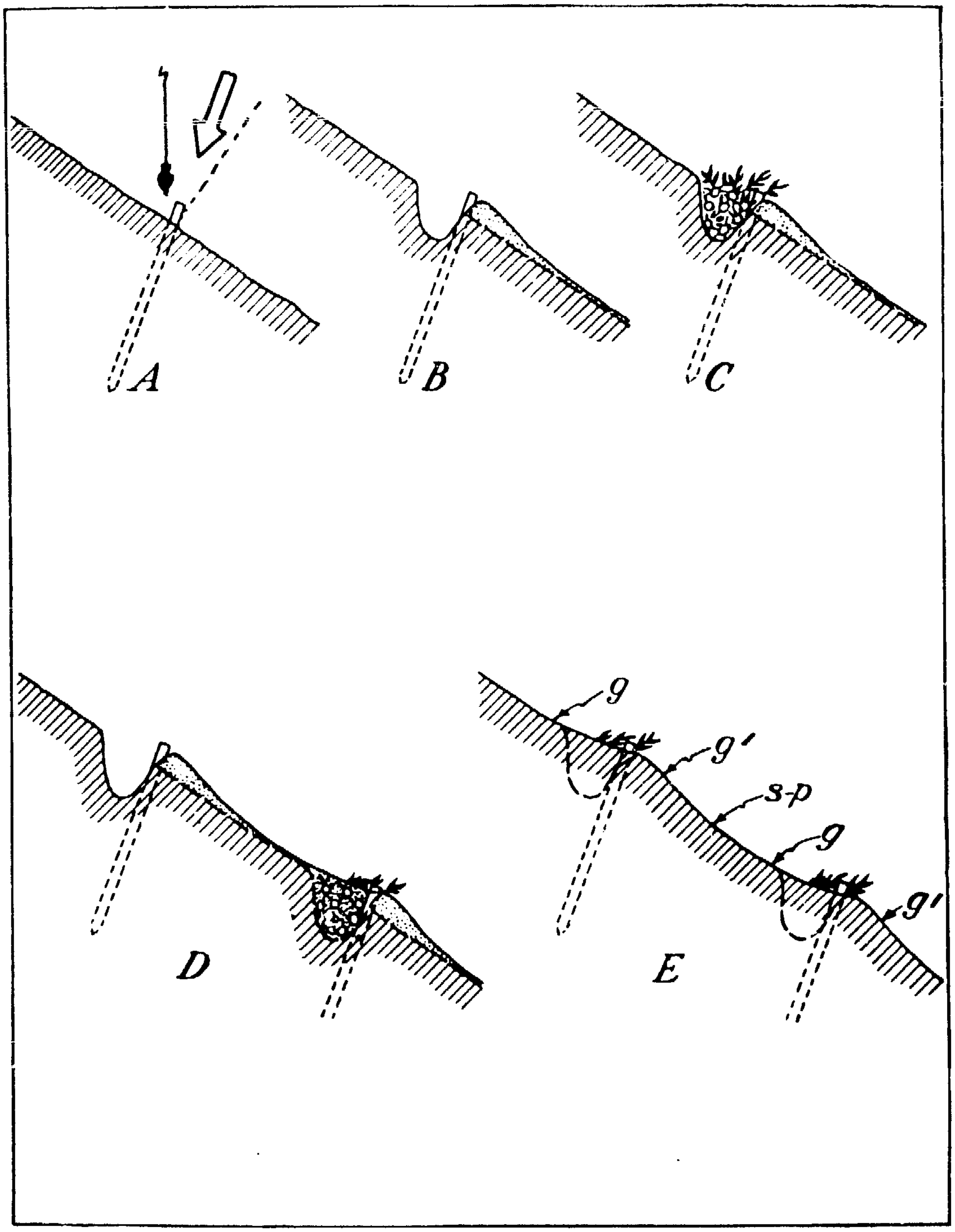

Figure 1. Procedures of Wattling and Staking. Steps in contour wattling and planting: A. Stakes set in contour rows, showing approximate angle of the stake which bisects the "plumb bob" line and a line at right angle to the slope. B. Trench cut just above the stakes. C. Brush wattles packed into trench resting against stakes. D. Lower contour completed, with brush wattling partly buried by soil from next trench above. E. Sowing and planting; cereal grains are sown at g (and at g' in extremely loose soil or where wattles are 4 feet (1.25 m) or farther apart): native seeds or plants are set at s-p. (From U.S. Forest Service Handbook)

b) areas of poor road drainage, which may threaten the staked area;

c) a site with no soil left or with rock cover;

d) a site where natural vegetation already exists;

e) a low bank which will stabilize itself naturally in time.

(Repeat; these are the areas not generally appropriate for application of the technique.)

3. THE METHOD

A brief description of the method, step by step, is as follows:

The best time to apply this treatment is in the winter or early spring, when the stakes are dormant, and a little before the rainy season.

3.1 Land Preparation

Shape the fill slope from the top to the bottom. Small rills or gullies should be filled in and rocks or tree branches removed or placed at the toe of the slope. Diversion ditches may be needed for longer slopes.

3.2 Staking

Guided contour lines should be laid out on the slopes. Staking should be started from the bottom of the slope upward with intervals of 1.2 m (or 4 feet) between rows and 0.5 m (or 1.6 feet) within each row. A hectare requires about 17 000 stakes (or an acre about 7 000 stakes). The length of the stakes depends on the overcasting material on the slope: 1 m or 1.2 m (3 or 4 feet) length is desirable. The stake diameter should be 5 cm to 6.5 cm (2 to 2.5 inches). All stakes are sharpened at the bottom ends.

The correct angle for driving the stakes through the fill is approximately the bisection of the angle between the "plumb bob" line to the earth surface and a perpendicular to the inclined slope (see Figure 1 example). To avoid splitting, a piece of strong wood should be placed on top of the stake when it is being driven in. Driving it in should be done gradually and cautiously. The stake should be driven through the fill and into the original ground. A maximum of 15 cm or 6 inches is allowed to stick out of the ground. Any split ends should be sawn off. One third or one fourth of the stakes should be of those species which will easily sprout and grow. The following are some species which have been used successfully for this purpose but, of course, the possible species vary from one region to another.

Lagerstroemia subcostata
Glyricidia sepium
Mallotus japonicus
Cassia siamea
Salix spp.
Bambusa spp.

It would be ideal if every fourth stake to be driven in a contour row is a live stake made of those species which can sprout and grow in the future.

Figure 2. Wattling and staking done under the special Employment Programme along a forest road, Mt. James Forest District, Jamaica, 1975 (Photograph made by the author shortly after work completed)

Figure 3. For comparison sake, an example of the somewhat different style of wattling and staking ("clayonnage") more commonly known in the European countries. (Photo: U.S. Forest Service)

3.3 Trenching and Wattling

A contour trench of 20 cm (8 inches) wide and 25 cm (10 inches) deep should be dug against or immediately above the contour stakes (Figure 1). Wattling bundles of 13 cm (5 inches) diameter and 3 m (10 feet) long should be put into the trench overlapping end and tail. This work should be done from the bottom of the slope to the top. The wattling bundle should not be completely buried into the trench but should be left with part of the branches and leaves above the ground to serve as a buffer strip. The trench and the nearly buried bundles serve at least three purposes:

a) to intercept the runoff and reduce its velocity;

b) to act as a barrier or a buffer strip for controlling rill or gully formation; and

c) to conserve moisture for stake growth.

3.4 Seeding and Planting

If necessary, grass and trees could be planted to speed up the protection of the fill slope. In areas where live stakes are not available these practices are necessary.

4. THE CREW AND EQUIPMENT

The stakes should be cut, sharpened and ready along the site. If the brush wattles are also ready, a crew of ten men would be sufficient as a working unit as follows:

- Staking, 1 holding stake and 1 driving (3 teams)	6
- Trenching and burrying wattles	2
- Transport of material, contouring, etc.	2

The following are tools needed for a 10-man crew:

- Hand level	1
- Wooden hammer or mallet	3
- Hoe	2
- Axe	1
- Hand saw	1
- Cord or wire and wooden board	

On very steep and long fill banks, a simple cable system should be set up for transporting the material and a safety rope should also be used for going up and down the slope.

On the average, a well organized 10-man crew should be able to treat 200 m^2 to 250 m^2 (or 2 000 to 2 500 sq ft) a day. A kilometre of new road may only have perhaps one hectare or more which needs to be stabilized by wattling and staking.

5. MAINTENANCE

It is important to inspect the staked area during the first rainy season. Any runoff coming from the road surface above should be diverted away by building a contour dyke along the road shoulder (or berm). Any breaks should be repaired and strengthened to allow re-vegetation to take place.