A STUDY OF THE RELATIONSHIP BETWEEN SOIL AND QUANTITATIVE TERRAIN FACTORS

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ABSTRACT

The objective of the study was to determine whether or not different soil areas in Hawaii could be separated by means of quantitative terrain factors. Eight great soil group areas on Oahu and six soil association areas on Kauai were selected. A sufficient number of 0.5-mile square test cells was established at random in each of the soil areas. Ten terrain factors were quantified in each of the test cells from data measured on either the topographic maps or the aerial photographs or both.

The results showed that certain great soil groups on Oahu and certain soil associations on Kauai can be differentiated by their quantitative terrain factors. Average elevation, local relief, average slope, slope length, land texture ratio and drainage density were found effective in differentiating between these different groups and associations. Four terrain factors has been found effective in separating the Haplustox, Eutrorthox and Gibbsihumox areas on Oahu. These factors, in the order of decreasing effectiveness, were average slope, drainage density, slope length and local relief. The discriminant function equation developed for Tropohumult and Gibbsihumox areas, based on average elevation, average slope, slope length and drainage density, has satisfactorily segregated the two soil areas on Oahu.

The results of the numerical grouping analysis of 108 test cells established in 0.5-mile grids in eastern Kauai indicated that numerical methods on the basis of several terrain factors has much to offer in reconnaissance soil surveys of large, relatively undeveloped regions where information about the soil is not available.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Many aspects of physiography have clear local or regional correlations with soil differences. Many pedologists have realized that soil distribution and development are closely related to topography. Jenny (1941), for example, regards topography as one of the five soil forming factors. Ellis (1932) introduced the concept of the hydrologic sequence in which soil properties vary in a regular way depending on the natural drainage controlled by the degree of slope.

The complicated and irregular distribution of soils geographically has led soil surveyors to use mapping units which are actually composite units. The catena of Milne (1935) was introduced just for this purpose. The "natural land type" of Wright (1958) and the "soil landscape" proposed by Woodyer and Van Dijk (1961) are further examples of efforts made to find more satisfactory soil mapping units in special circumstances.

The shape of the land surface changes so much within the distances of a few tens or hundreds of feet that the pattern of soil is generally complex. Experienced soil surveyors realize this and rely heavily on visual interpretation of landscapes for predicting the types of soil present and the locations of soil bodies. Such visual interpretations are more of an art than a science and, therefore, the soil maps produced by one surveyor can be expected to differ in detail from those produced by another surveyor for the same area. This situation will remain true as long as the interpretation of landscape remain qualitative.

Several qualitative and semi-quantitative terms are used to describe landforms. Such terms as level, sloping, rolling and hilly are useful for describing the setting of a soil. Concave, straight and convex are terms that help to describe the nature of a specific slope. Slope gradient and length of slope have been placed on a reasonably quantitative basis.

The Problem

The problem of land utilization in most of the developing countries assumes more and more importance as population increases and material civilization advances. The problem of raising the productivity of the soil assumes increasing urgency and basic research is a necessity for planning and for efficient implementation of appropriate projects. Knowledge of the soil is of paramount importance in any project aiming to improve the agricultural sectors of the country.

Many developing countries lack the resources, financial and human, even for the reconnaissance soil survey of the country. These countries are constantly seeking for a speedy way of undertaking reconnaissance soil survey, a technique which will require only a minimum number of trained personnels at a cost the government can afford without jeopardizing other projects. Most of these countries undertake soil mapping by using planimetric map as a base. Planimetric maps do not include many features on the ground. Mapping soils using such map is slow and plotting soil boundaries is very difficult and often low in accuracy.

A soil survey starts with a general inspection of the area in order to get an appreciation of a broad soil pattern in relation to the geographic location and the characteristic landscape of the project area. It is only after a soil surveyor has gained a good picture of the general run of the country that he plans the pattern of his traverses and his inspection sites. His problem of determining where to draw soil boundaries is solved by augering and digging of profile pits in combination with a study of the landscapes. Rarely has a surveyor time to determine each single length of a soil boundary by boring holes at both sides to prove that the soils are truly different. Normally, the soil surveyor relies upon his knowledge of the correlations between soil profile differences and soil landscape changes, and a good surveyor is the one who knows about this correlation and knows how to represent it on a piece of paper which is going to be the soil map.

Physiographic considerations have not always received the attention they deserve in taxonomic soil classification but they are certainly of vital importance in soil mapping. Within a landscape two soils may differ very greatly in their profile properties and yet, because they are closely related genetically, may have important properties in common. Classification of the landscapes, however, has always been a problem to soil surveyors. The geomorphological genetic classification is not difficult in certain types of landscapes, such as depositional landscapes of alluvial or aeolian origin. But in many erosional landscapes, genetic classification is often a problem. As an alternative the morphometric approach can be applied in which landscape are classified according to measurable characteristics. Slope, length of slope, density of gullies, depth of gullies, etc., can all be measured and expressed in numerical values and classified.

It has been established that aerial photographs interpreted by competent operators can give very good results in the qualitative prediction of some of the soil properties, for example, texture, drainage, depth to bedrock, type of underlying rock formation, etc.

(Belcher, 1943, 1950; and Parvis, 1950). These workers have used aerial photographs in their study of soil under the premise that photograph is a record of the results of natural processes which present a pattern which can be correlated with the soil forming factors. If soils have qualitative patterns which can be examined on aerial photographs, quite likely there are also quantitative patterns. The problem is to determine how to find and evaluate these quantitative patterns.

If it can be established that there is a relationship between quantitative terrain factors and soils, this study will be of much value to underdeveloped as well as developing countries in terms of providing informations on the use of aerial photographs and/or topographic maps in reconnaissance or semi-detailed soil survey.

The Objective

The principal objective of this paper is to determine whether or not quantitative terrain factors which can be used to differentiate soil areas exist in the study areas.

The principal objective was approached in the following general steps:

1. Determine the parameters which can be used to characterize terrain units quantitatively with respect to both landform and fluvial features and where measurements can be done on vertical aerial photographs and/or topographic maps.
2. Determine statistically whether or not some soil associations mapped on Kauai and some great soil groups established on Oahu can be separated by means of the selected terrain

factors; that is, to determine whether there is relationship between terrain features and soil boundaries.

3. Evaluate by various terrain statistical techniques, using the computer, the factors applicable in mapping soils of a portion of Kauai island.

While the terrain is a measurable reflection of the soil forming processes, the purpose of this study was not to investigate in detail each layer of the soil profile of each of different soil areas studied and explain its formation. No attempt was made to explain why the landforms involved have specific shape though it was assumed that various volcanic activities and erosional processes have important roles in shaping them. Terrain was considered to be a factor influencing the nature of soils, but the factors that influenced the terrain were left for other studies.

Reasons for Quantifying Terrain Factors

The study of geomorphic and other terrain features by quantitative methods has developed in recent years into a new and fruitful scientific endeavor. Quantitative method of analysis has been applied to geomorphology with considerable success, yielding important informations regarding the nature and intensity of many natural processes. However, while many persons (for example, geographers and geomorphologists) are engaged in quantitative investigations of one kind or another, they commonly find themselves working in ignorance of the persons belonging to another scientific discipline and utilizing terrain informations considerably. For instance, the quantitative terrain factors analysis has not been applied completely to soil survey work although many pedologists are aware of the importance of such analysis to soil classification. Except for the measurement of elevation and slope of the land, terrain is most commonly described by such qualitative terms as "gently rolling," "rugged," "dissected by deep gullies," etc. Perhaps one of the most important reasons why terrain quantification has not really gotten its foothold in soil classification is that the literature of this new field is so diffused among journals of many scientific fields that only by great effort can an individual become aware of all aspects of development.

Comparison of pedologic and topographic maps often show an obvious relation between the boundaries of different soil associations and boundaries which can be inferred from the change in character of the terrain as represented on the topographic map. The boundaries between different soil association may, for instance, coincide with a change in density of contour lines or in number and length of streams or some other terrain factor or combination of factors. To evaluate this relationship the terrain factors must be represented by numbers and not merely in qualitative terms as usually practiced by soil surveyors.

The earliest attempt to describe the character of the form of the earth's surface was essentially in terms of qualitative descriptions of the terrain. Qualitative description can have different meaning to different observers who have different experiences. In addition, qualitative description are not applicable to statistical analysis nor can they be used with modern data processing equipment.

If the relations between soil and terrain factors is significant, one of the most practical applications would be to coordinate the quantitative relationship between terrain factors and the engineering classification of soils with the automatic scanning device that convert aerial photograph patterns to quantitative terrain data by means of the electronic computer. Appropriate programs would link the scanner and the computer and give a direct read-out of the engineering classification of soil areas included in the aerial photographs. Shelton (1968) in his operation manual for New York State land use and natural resources inventory displayed the inventory data by means of Synagraphic Mapping System devices developed at Harvard Laboratory for Computer Graphics.

Soil Forming Factors and Topography Forming Factors

The terrain or surface features of the earth are a reflection of the materials of which it is composed and forces acting on those materials. Geomorphologists state this idea by asserting that the characters of landform are controlled by structure, process and stage (Thornbury, 1954). The pedologist's concept is that the characteristics of a soil are principally a function of climate, topography, parent material, vegetation and time (Jenny, 1941). Although the two concepts differ in terminology, the soil forming factors and the topography forming factors can be correlated in the following manner:

Soil Forming Factors	Topography Forming Factors
Parent Material	Structure
Topography	
Climate	Process
Vegetation	
Time	Stage

While the soil and topography forming factors are not perfectly related it is apparent that substantial relationship between the two forming factors exists. The basic assumption in this dissertation is that the soil and the topography forming factors are related. If this assumption is true, the soil and terrain at various locations with similar soil and topography forming factors will have properties different from those of other areas which developed under other conditions of environments and parent material.

REVIEW OF LITERATURE

General

Standards for soil surveys in the U.S. have been established by Soil Survey Staff and published in the Soil Survey Manual (1951). They define land form as "an essential part of a soil, conceived as a three-dimensional landscape resulting from the synthetic effect of all the materials and processes in its environment. Kinds of soil profiles are associated with the kind of land form that influence their genesis". This manual suggests that various slope ranges be used in defining soil mapping units and points out the need for describing other features of slope but leaving them to be described qualitatively.

Cline (1961) applied the terms uniform, convex and concave to the slope profiles. He defined convex slope as one where the slope gradient increase as you go downhill. Water flows faster farther on slopes like this, and the soils are almost always well or moderately well drained. On a uniform slope profile, the slope gradient is constant going downhill. On a concave slope, the gradient decreases downhill. On this type of slope profile water concentrates because the rate of run-off decreases as the water flows downhill. Such slopes commonly have poorly or imperfectly drained soil.

Hack and Goodlett (1960) divided the contour forms on topographic map into three groups designating them as the "nose" of a hill where contours were convex outward, the "side" slope where contours were straight, and the "hollow" where contours were concave outward. In the "nose" position any water running downslope tends to diverge proportional to a function of the radius of curvature of the contour. On the "side" slope the flow of water over the ground must be proportional to the length of the slope. In the "hollow" position the amount of water passing over the surface is proportional to a quantity considerably greater than the slope length.

Arnold et al. (1960) presented the estimates of slope classes in Iowa made from randomly selected samples which made up about two percent of the land area of the state. The authors suggested that there was an apparent relation between soil type and slope but cautioned not to draw conclusions from the slope data alone.

Horton (1945) studied the tendency of soil to erode and concluded that every type of terrain has certain minimum length of slope required to produce enough runoff and cause erosion. He considered this slope length as the critical length which is dependent upon ground slope, runoff intensity, infiltration capacity and susceptibility of soil to erosion. He suggested that by considering such factors and determining a proportionality factor it should be possible to predict the amount of erosion that would occur at a particular place and time. The Agricultural Research Service (1961) have done some efforts along this line of study for soil conservation purposes. Slope length and slope gradient have been considered in these efforts but complete landform description has not been made.

Ruhe (1950) showed that frequency curves of slopes in Iowa taken along traverses, such as roadways, have distinctive shapes for different stages of glacial drift. He divided each traverse into approximately 100 equal increments and determined the slope gradient of each. The gradients were grouped into slope classes and the results were plotted as frequency curves. He found that relative frequencies of the slope classes are related to the age of glacial drift and to the age of soils.

Walker et al. (1968) in their study of the relationship between landform parameters and soil properties in Iowa showed that generally, elevation and slope were most strongly related to the morphological characteristics, such as, thickness of the A horizon, depth to gray mottles, depth to reddish or brownish mottles and depth to carbonate horizon. Slope length direction was also found to be an important parameter for the A horizon thickness and subsoil mottle features. Data on terrain factors were recorded with soil profile observations across small loess and drift landscapes. Simple regression and correlation analyses were used to study the relationship between each soil property and terrain factors.

The preceeding references indicate that gradient, length and shape of slope are important features in soil development. However, Jenny (1941) has noted that as "soil-forming factor topography is of a complex kind, for it includes, in addition to degree of slope, shape, length and possibly exposure and certain hydrologic feature commonly referred to as drainage".

Vadnais (1965), in his study of the quantitative terrain factors as related to parent materials and engineering properties of soil, showed that certain glacial soil association areas in North Central U.S. can be differentiated by their terrain factors. These soil association areas have different engineering properties of B and C horizons. Within the area of study, he noted that terrain factors such as average slope, roughness index, cell relief and slope changes per mile of traverse were the most efficient among the 14 factors he measured in separating soil association areas in Illinois-Indiana-Wisconsin glaciated area. In a large percentage (86-89 percent) of the comparison studied, Vadnais found that there was a significant difference between the values of the quantitative terrain factors for the pair of soil areas being compared.

History of Terrain Quantification

Quantitative descriptive studies are not new in landform literature. Neuenschwander (1944) reviewed and summarized the literature concerned with morphometric studies published up to 1944. He defined morphometry as a study concerned with the development and application of methods which enable us to describe precise characteristics of landscape in quantitative terms.

The earliest quantitative factors used to describe the land surface were slope and relief measurements. The actual slope of land was first suggested by Penck (1894) as a pertinent factor in geomorphic study of a region. He proposed that the characteristic slope be determined by weighing the slopes of various parts of the region in proportion to their respective total area.

Finsterwalder (1890) was the first worker who suggested that the average slope may be found by multiplying the total length of contour lines contained in a given area by the contour interval and divided by the given map area. Since the method was based on the total length of contour lines, Finsterwalder technique was suitable only for measurement on maps with few, widely spaced and relatively smooth contours. Rich (1916) proposed a simpler method of determining average slope. A network of profiles was drawn at right angles to the contour lines. The sum of the differences in elevation along the profiles divided by the total length of the profiles represent the average slope of the area. The method proposed by Rich is less laborious and more applicable to complex types of terrain but it is still very time consuming.

The most widely known and used method of determining average land slope is that proposed by Wentworth (1930). A brief look at his method shows that it is much simpler to use and applicable to the most intricate topographic maps and yields results of any desired accuracy depending on the accuracy of the map and the number of traverses used. A grid of at least three pairs of lines perpendicular to each other is drawn, the number of contours crossed is counted, the length of all lines is measured, and the number of crossings per mile is computed, multiplied by the contour interval, and divided by a constant, 3361.

Hook (1958) used Wentworth's method in suggesting another terrain factor which he called a "roughness index". He described this terrain factor as being an indication of the density of contour lines. He computed three sample areas in Ohio where smooth topography gave him a roughness index of 4.1 while rough topography had an index of 34.1. The roughness index was used by James (1961) to distinguish various Wisconsinan substage in Indiana. His work showed average roughness indexes of 10.0 for Early Tazewell, 3.2 for Late Tazewell, and 4.2 for Cary areas.

Most studies on local relief that have appeared in the American literature since 1935 are based on the simple method proposed by Smith (1935). He defined local relief as the difference between the highest and lowest elevations within the unit area. Smith prepared a local relief map of Ohio based on 1:62,500 topographic maps and 5-minute rectangles. He obtained nearly 2,000 values and from these values an isopleth map was drawn with a constant interval of 100 feet. Smith considered this local relief map only a substitute for a slope map. He felt that slope is the most revealing and important aspect of terrain. However, because of inherent complexity of the area, slope can only be measured on very large scale maps and only for small areas. For large areas, the local relief map seemed more suitable. It reveals certain slope characteristics and at the same time is easier to prepare.

Traditionally, the physical characteristics of different regions have been described verbally or shown on hypsographic or physiographic maps. An analysis of surface configuration based on empirical, quantitative description has been slow in coming. Veatch (1935) proposed a quantitative and graphic method for summarizing the characteristics of different types of landform. He divided the total surface configuration into: (1) highland--as top of a knoll, crest of a ridge, tableland of high plateau; it is relatively level area, (2) lowland--as a valley bottom, a basin or any other kind of depression, and (3) slope--surface connecting the highland and the lowland. Linear traverses were drawn on topographic maps and the total percentage of their length representing the highland, the slopes and the lowlands was computed and plotted on a graph. The resulting profile-graphs distinguish between areas which differ in the total amount of upland and lowland and the average steepness of slope connecting the two. It is a highly generalized method but it is based on quantitative measurements and can be used for comparative studies.

Wolfanger (1941) further elaborated Veatch's method by substituting the word "supraplane" for the lowland and "infraplane" for the upland (both having 0 to 3 percent slope) and slope was broken into four classes: B--gentle slope (4-7%), C--moderate slope (8-15%), D--steep slope (16-25%) and D--very steep slope (greater than 26%). The landform of a given region was analyzed in terms of these elements and the data were summarized in the graph. This graph shows the infraplane, the supraplane and the slope of different degrees of inclination as lines of appropriate lengths and at appropriate elevations. Like Veatch's method, Wolfanger obtained his data from traverses drawn on topographic maps.

In general, Veatch's and Wolfanger's attempt to present quantitatively a total inventory of the land was commendable. But both methods suffers all the weaknesses of an average. Their graphs represent a summary statement and do not show any internal variation.

A fully systematic approach of empirical landform analysis based on the identification and use of its inherent characteristics and resulting to a quantitative map of terrain types was proposed by Hammond (1954). His classification of terrain was patterned after those applied to climate, soils and vegetation.

Another systematic and quantitative method for analyzing landform characteristics and delimiting landform regions was suggested by

Wood and Snell (1960). Landform data were collected for selected sample areas on 1:100,000 topographic maps and stored on cards.

However, by far the largest volume of work done in connection with terrain quantification are those which concern with measurements of hydrographic and fluvial geomorphic properties of the land surface. Under the pioneering work of Horton (1932) and the leadership of Strahler (1947), a group of geomorphologists has been trained in the development and the use of quantitative techniques suitable for analyzing drainage basins. The purpose of their studies was to analyze the processes which are shaping the landform of the drainage basin and to discover the laws governing the relationships between these processes and the resulting terrain.

Individual Units for Soil Survey

Soil survey includes the separation of landscapes into soil mapping units and describing these units in quantitative and qualitative terms. In the course of soil survey, soils are studied, identified and delineated in the fields. Individual soils may be taken as the soil mapping units or they may be conveniently combined into soil associations or to other units. This section discusses the individual units which have been proposed and/or used for soil surveys or land studies in various parts of the world.

The following discussion is a result of extensive review of literatures made on the subject. There are ten individual units for soil surveys presented:

1. Catena
2. Geomorphic Surface
3. Ground Surface
4. Land Component
5. Land System
6. Pedomorphic Units
7. Polypedon
8. Soil Association
9. Soil Body
10. Soil Stratigraphic Unit

Catena

Milne (1935) introduced the word catena as a mapping unit to describe patterns of contrasted soils associated with undulating topography in East Africa. He defined catena as "a regular repetition of a certain sequence of soil profiles in association with a certain topography" and stated that the distribution of soils in a catena is a function of differences in level. He said that where the rock is uniform, soil differences are brought about by drainage combined with reassortment of eroded materials and constituents leached from above.

Since Milne's definition, there had been much discussion as to whether the component soils of a catena need to be associated geographically in a continuous sequence. This discussion resulted in Bushnell's (1942) redefinition of the catena to include soils of all possible hydrologic situations on a given parent material, under a uniform climate, whether or not the soils were associated together in a continuous sequence. He suggested a taxonomic theory in which catenas were groupings of soil genera and mentioned that in mapping practice catenary complexes represent certain associations of soil types. Based on his redefinition, Bushnell mapped about eight different soil catenas in parts of Indiana.

Milne introduced catena as a mapping unit. However, since the occurrence of contrasting soil units associated with the undulation of the landscape is very common, catena cannot be suggested as a mapping unit in better soil surveys. In reconnaissance soil surveys of large areas, however, catena can be used as mapping unit. In such surveys, catena would represent constantly occurring associations of soil units. In tropical regions, for example, the sequence of red soils on the hills, changing gradually to yellow and then to gray and finally black in the lower parts of the landscapes is a characteristic sequence which occur repeatedly in some regions. Such mapping units do not have straight forward relations to the units of the soil classification systems.

Bushnell's catena is very useful where drainage is more variable than parent material or climate. In some areas of Europe, however, the catena has been found to be too broad as a map unit even in reconnaissance soil survey. The reason for such a behavior is not clear. In the U.S., the catena usually includes several soil series, types and phases. The catena was named after a "normal" or central soil series found within the catena. It appears to have only very little difference from the soil association as a mapping unit. The soil association is established to include all soils regularly found to occur on certain landscapes. The soil catena is formed with more strict adherance to a central criterion, such as variation in drainage and position in the landscape. Also, unlike some map units, catena requires that the members will have similar parent material and climate.

A field catena may be as large as the area under survey although the extremities may have to be sought outside it to explain what lies in between. Presumably, the physiographic drainage basin is the maximum extent of each catena with almost endless minor catenary variations within it.

The catena, in its simplest case, would consist of a topographically determined set of soils, originating from the weathering of a single parent material under the influence of normal erosion, the essential feature being the mechanical fractionation and elutriation of the weathering products down the slope by the action of rainfall. In older and highly developed situation, the lower soils of the catena would be largely affected by further differentiation of the fractionation products under the influence of their topographic situation, so that they can be considered as related only indirectly to the parent material. These soils would also be affected by the influx of the soluble materials, especially bases from up the slope. Thus, as a major pedogenic factor, normal erosion leading to the differentiation, under constant climatic conditions, of several but related soils from a common original material, would be an essential feature of the catena mapping unit.

Geomorphic Surface

A geomorphic surface is a landscape surface on which the soils are forming or are in equilibrium. Ruhe (1956) recognized several geomorphic surfaces in Iowa. In a way geomorphic surface may be considered as remnants of former catenas and which are now dissected. Hence, it may be expected that there should be or should have been one or more soil series associated with the surface. Due to geologic processes the original characteristics of the older paleosols would be masked or destroyed and some original characteristics such as cation exchange capacity, base saturation, organic matter content and pore space must be inferred. There may or may not be one or more orders associated with the surface.

The purpose of using geomorphic surface as soil mapping unit is to understand or at least to gain insight into the pedogenesis of the area and the history of the soil forming periods and how they relate to the formation of soils. The characteristics for identification and separation of geomorphic surface are regional surface slope and topography, slope breaks, pebble surfaces and aspects of the profiles on the surface. The units may be crudely mapped out merely by observing abrupt and laterally persistent slope changes and/or vegetational changes. The geomorphic surfaces in its present distribution is usually related to the present drainage system and with the older surfaces on interfluves or upland drainage divide. The younger surfaces are exposed topographically lower or closer to the drainage system.

Ground Surface

Butler (1959) defined ground surface as those erosional and depositional surfaces and layers which have developed in a landscape during one interval of time (K-cycle) and upon which a unit mantle of soils has been developed. The time interval involved in one K-cycle includes the time of deposition of a new surface layer, the time of soil development, and a time of renewal by erosion or deposition.

Basically, the ground surface is the unit of mapping for the purpose of soil classification along natural boundaries; in this case layers homogenous in erosional history in a given continuous interval of time. Many soils are classified on a geographic concept, such as, the association of the land with topography, climate and vegetation. The ground surface concept permits an independent study of soils from a pedological point of view, based on the fact that soils developed on exposed landscape surfaces. This, however, is not entirely true because soil development does proceed throughout the depth of the solum. Thus, the condition of formation, persistence, and destruction of landscapes can be studied more easily. From the practical point of view, correlation between landscape and soils can be made since "recurring relationships exist between certain types of soil mantle layering on hillslopes and topography".

The criteria originally used to recognize material belonging to one ground surface were: (1) lateral continuity of soil layer in terms of particle size, (2) lithology of the parent material, (3) continuity of stone lines, and (4) pedogenetic differentiation of sola; for example, the degree of contrast between A and B horizons, the type and degree of development and organization in lower B horizon (Butler, 1959; and Van Dijk, 1959). However, Van Dijk et al. (1968) stated that these criteria were often not sufficient in the field to recognize what they believed to be the true ground surface. They found that the degree or presence of gleying and differential weathering below the solum, stratigraphic position of the alluvial segments in a given section of layered ground surfaces, and the degree of connection between the alluvial and upland components of the ground surfaces were better diagnostic criteria in the area they worked.

Ground surface system has been developed and used in Eastern Australia. Butler and Van Dijk (1958, 1959) studied the Southern Tablelands region around Canberra and Walker (1962) used the concept in South-Central New South Wales where he found pedologically unmodified deposits due to effects of clearing and cultivation as a separate ground surface. Although the system originated and has been used in Australia it has been utilized in part in Central U.S. (Thorp et al., 1951).

Ground surface concept would likely be too broad and not too discriminating in areas which are not characterized by numerous cycles of erosion, deposition, development and renewal or where previous layers are too deep to be easily accessible or traceable. In addition, the system has little or no consideration for vegetation as a factor of soil formation. Only the effects of parent material and topography are considered as influencing factors.

Land Component

Land component as used by Gibbons and Downes (1964) in Eastern Australia refers to an area where the climate, parent material, topography, soil and vegetation are uniform within the limits significant for a particular type of land use. The unit is used for the purpose of identifying the smallest mappable land unit homogeneous for a particular land use and thereby serve to construct plans for land use. The boundaries are dependent on the land use for which the map is made but are usually at least partially related to some environmental factors.

The criteria used to separate land components include potential productivity, return per acre, yield or rate of stocking, developmental methods (type of cultivation, species used, etc.), present erosion, risks or erosions and economics.

The land component unit does not necessarily coincide with natural soil boundaries. Soils are grouped into orders, groups within orders and sometimes subgroups and soil types. The lowest soil division recognized will ordinarily be used to define a land component, unless other criteria are still smaller. Thus, land component may differ due to depth of solum.

Since land component is defined in terms of land use, its lower size limit is the smallest manageable size of a crop, or the minimum area to which a farmer can give different treatments. Presumably the lower limit could also be defined in terms of other land use plans, such as the smallest feasible size for rubber plantations, or for houses.

This system is used for surveys designed to make land-use recommendations. It has been applied in Eastern Australia with major studies in Central-Western and South-Western Victoria. Most of the mapping is done by aerial photographic techniques with much less field reconnaissance than using ground surface as a unit.

Land System

Gibbons and Downes (1964) and Sibley (1967) used land system in their studies of land in Australia. Land system is an area made up of limited number of land units which are related on the basis of features considered to be important for the likely land use of the area. Thus, land system is identified and separated from geographically adjacent map unit on the basis of characteristics important for the land use of the area. Landform and geology are most commonly used. As mapping unit, the land system is part of an ecological survey system which considers the influence of climate, parent material, topography and soil acting together.

Soil is only one factor in the system so that its relation to a soil classification system is only indirect. However, soils are classified to the subgroup or family level. Surveys using land system mapping unit provide an orderly basis for subsequent surveys, indicate the priority of further attention and give fundamental information on soils and geology.

The land system is applicable to surveys of large areas where traverses are made about ten miles apart. Surveyed areas are mapped at a scale of four miles to the inch.

Pedomorphic Units

Dan and Yaalon (1968) used the concept of pedomorphic surface and pedomorphic form. They defined pedomorphic surface as a landscape presenting soils and relief genetically and evolutionary interdependent. The workers stated that in such a landscape it is possible to recognize various soil profiles with a definite horizon sequence, reflecting the nature of erosion and sedimentation processes and the maturity of the soils. Such profiles representing the various catenary members of the pedomorphic surface are called pedomorphic form.

A pedomorphic surface is characterized by genetic age (young, mature), erosional history (depositional, erosional), and source of parent material (relic, polygenetic). Pedomorphic forms are sometimes subdivided into phases differing in one or only a few characteristics like genetic age or stage in erosional history.

The system was developed in an arid region of Israel and thus seeks to recognize natural soil units based on water regime, extent of erosion and nature of deposition, because erosion and alluvial and aeolian deposition are important in arid regions. There were fourteen pedomorphic forms recognized and defined in Israel.

Horizon sequence, topographic location and erosional history are the characteristics stressed in defining pedomorphic unit. Other characteristics which are used to define the units are: (1) presence or absence of lithic discontinuities, (2) relative position of the water table at different times of the year, (3) general nature of the climate and (4) extent of present erosion.

The general purpose of the unit is to recognize natural soil boundaries which separate the mantle into units which presumably possess differences important for the land use of the region. The size or scale of a unit will depend on the amplitude of topographic variation in the environment and will be generally the same size as the member of a catena (Bushnell, 1943). Thus, if the topography is windblown sand dunes, one pedomorphic form is likely to correspond to the scale of one slope, or to the hummock top, or the depression depending on the number of divisions recognized.

Pedomorphic form is new and has not yet been related to natural soil classification system. However, since pedomorphic forms are separated by differences in erosional history, topography and its subsequent effect on soil forming processes, the forms will correspond fairly closely to "natural" soil boundaries and would likely correspond to a single catenary soil unit in a natural soil classification system. Topographic boundaries could be readily traced from aerial photographs, but erosional history would require extensive field reconnaissance, just as in the case of Butler's ground surface.

Polypedon

The polypedon is defined as a real physical body of soil including one or more contiguous pedons, all of which fall within the defined limit of a single soil series (Soil Survey Staff, 1960). Polypedon is the basic soil individual in the taxonomy of the new U.S. Comprehensive Soil Classification System; that is, they are real objects that are placed in classes of the lowest category. They are comparable to the individual mango tree, individual fish, and individual man. In ascending order, the polypedon is grouped into soil series, the series into families, these into subgroups, these into great soil group, then to suborders, and finally to soil order.

Polypedon is sufficiently large to include all the criteria for being "a soil" including the features (landscape) and boundaries with adjacent "non-soil" and/or distinct polypedons. Polypedons are intimately related to the entities delineated on soil maps, but in most instances they are not identical. Soil mapping units comprising polypedons would consist of one polypedon plus some "impure" bodies;

that is, the pedons and polypedons of unlike soils--the so-called mapping inclusions. The maximum allowable percentage of these inclusion is 15 percent.

Where the soil is relatively uniform the polypedon may include a large area, perhaps over 10 acres. In this situation, the map units may subdivide the area by constituent soil types or soil phases. In an area of more variable soil, the small area of the polypedon may result in the combinations of certain polypedons such as soil complex, or a soil association, for a given map unit. Inasmuch as polypedon is the soil of a given geographic location and is sufficiently uniform as defined by the classification system, it may frequently coincide with certain soil association as established for that area.

As the central taxonomic unit in the new Comprehensive Soil Classification System, polypedon have clearly defined limit. These limits vary depending on the criteria assigned for the specific type of polypedon considered. For example, a separate set of criteria and boundary concepts are used to separate two distinct polypedons of an Entisol vs. two distinct polypedons of a Mollisol. However, the boundary between polypedons must be consistently recognizable in the field based primarily on features on the landscape, informations on soil genesis and in routine techniques which are functional in the field.

Few previous soil mapping has been done with the polypedon as the mapping unit, though this probably occurs coincidentally. Presumably, soil mapping in the U.S. today is based on this map unit. Although the influence of the new system is being felt in several other countries, it is doubtful whether any actual new mapping has been done using this concept.

Soil Association

The soil association, as a mapping unit, can be defined as a group of defined and named taxonomic soil units, regularly geographically associated in a defined proportional pattern. It is a group of soils with or without common characteristics, geographically associated in an individual pattern. Soil association is the principal soil mapping unit shown on all small scale soil maps, including original surveys and compiled soil maps.

On relatively large scale reconnaissance soil maps prepared in fairly well known areas, the association are defined in terms of the same kind of taxonomic soil units used in a detailed soil survey.

At the soil series level, for example:

Kapaa-Pooku-Halii-Makapili soils

At the soil type level, for example:

Jaucas-Mokuleia sandy loam

On maps of small scale, great soil groups or soil families may be the units defined within the individual.

At the great group level, for example:

Red yellow podzolic-Yellowish brown lateritic
association (commonly found in Malaysia)

Soil association contains soils of at least two series which need not be related at any category in the system of classification although they would generally belong to the same class at higher categories in the system. It may be used as mapping unit in the original surveys of a region, as the Manawatu-Rangitikei Sand Country in New Zealand, or for generalized compilations from existing detailed soil maps such as the generalized soil map prepared by Soil Conservation Service for Hawaii State and used in this paper.

The main purpose of the soil association map unit is to remove all intricate and complex details which are not required in the map for the objective at which the survey is done. This makes the map easier and more convenient to read and to use. This is particularly true in small scale soil mapping where only some general features of the area being surveyed are required. For such objectives of soil surveys, the time required for field work is considerably reduced and, although fewer lines appear on the map, there is relatively little reduction in the value of the soil map.

As a mapping unit, the soil association can be used at several levels and for several objectives. An area may be mapped to indicate the association of certain soil series or phases of series relevant to the design of farm plan. On a larger scale, soil association may be helpful to a level of a "few farms" or for the whole rural communities or political subdivisions. At this scale, a given association may include widely spaced members of the overall classification system such as different soil series, soil families or great group.

In the new Comprehensive Soil Classification System of the U.S., it is possible that soil individual belonging to several different orders, for example, Entisols, Histosols and Alfisols could be regularly found geographically adjacent to each other, and could be mapped as single soil association.

The purpose of soil association as mapping unit is to show the occurrence of certain soil properties of special importance to a given geographic region without the inclusion of unnecessary details required by the overall system of classification. Therefore, it is clear that the soil association generally cannot coincide with the groups of taxonomic classification system, simply because soil association must be biased to properties of soil individual rather than to its geographic location.

Soil Body

A soil body is a segment of the irregular continuum at the earth's surface. It is a three-dimensional specimen of a taxonomic unit such as a soil type. The soil body may exceed 200 acres and may have extreme variability in outline, form and smoothness or roughness of the upper and lower surfaces. The lower and lateral boundaries depends on the judgement of the soil surveyor who takes into account the characteristics of the soil, nature of soil classification scheme, the degree of mapping and the intended uses of the soils and the soil maps.

A soil body has the following characteristics: (1) shape, (2) irregularities of the upper and lower surfaces of the solum, (3) slope gradient, (4) slope variation, (5) pattern, (6) natural drainage condition and (7) landscape position. Hole (1953) discussed the last three characteristics expressing them in terms of indices--pattern indices, natural drainage indices and landscape position indices.

> Pattern indices--The pattern index of a soil body is based on a circle. As the boundary line of a soil body departs from a circle, in plain view, the larger is the pattern index.

Narrow soil bodies with irregular boundaries have the highest pattern index.

Natural drainage indices--Hole arbitrarily assigned the value of 1 to well drained soils and 10 to organic soils. Extreme cases of excessively drained soils were given a value of minus 10.

Landscape position indices--The soil keys used in mapping soils in Wisconsin showed that each soil is classified according to parent material, vegetation, physiographic location, relative age, and a Bushnell (1943) natural drainage designation. In Bushnell's designation each soil is assigned a position from top to bottom in an imaginary hill. Soils representing an entire sequence is assumed to lie in a logical order although actually soil members may be discontinuous or even missing. These data are expressed in landscape position indices.

The purpose of using soil body as a map unit is to give the soil three-dimensional characteristics and to facilitate descriptions and comparisons of soils. The Comprehensive Soil Classification System may employ soil bodies as units; for example, the polypedon is a soil body, and soil types and soil series are thus units of soil bodies. Thus, Hole (1953) reports that the average acreages of soil bodies in Wisconsin, according to the soil series concept is as follows: Dubuque, 443; Spencer, 1,449; and Otterhold, 202 acres.

The soil body system can be used world wide if considered on the basis of the polypedon.

Soil Stratigraphic Units

Firman (1968) was not very clear in defining his soil stratigraphic units. It seems that he associated broad soil groups to stratigraphic units separated by geological method. A stratigraphic analysis of a region would give a good idea of the distribution of soils based on the stratigraphic layering of different materials.

A soil stratigraphic unit is considered to be a soil unit, usually one layer and not the whole profile, and subject to stratigraphic analysis. It is clear that a soil stratigrapher would be working with single horizons and the method would be geologically oriented. For this reason, it would be difficult under many conditions to compare these units with soil units as recognized by soil scientists.

Ruhe's (1956) paleo-planosols in Iowa are really soil stratigraphic units and have been treated as such. Soil stratigraphic units are not necessarily related to elevations on the landscape or to certain aspect of landscapes since these paleosols were formed presumably when there was a different base level and different geomorphic and tectonic conditions.

Stratigraphic analysis of a region are usually made for reasons other than soil studies. The soil scientist, however, uses such data widely in soil surveys. Therefore, the stratigraphic approach to soil distribution is really something that is constantly being used by soil surveyors. The recognition of soil stratigraphic units leads to an understanding of past soil forming environments, mainly climate and landscapes, and provides clues as to processes of pedogenesis in the past. However, without fossils it would be difficult to relate soil stratigraphic units to time stratigraphic units and where done it would be accomplished tentatively on the basis of stratigraphic position. Radiometric dating could be done but the necessary conditions for dating are not commonly encountered. It would be really under favorable conditions that pedons would be preserved and encountered by the soil stratigraphers. Geological forces acting on the paleosols made the soil stratigraphic units highly fragmented. Erosion could dissect the soils before burial and katamorphism could greatly modify its texture and composition with time. However, when recognizable units are encountered they can be classified in anything from soil series to orders.

Morphometric Properties of Drainage Basins

The characteristics of a drainage basin (or watershed) have been quantified by many geomorphologists and most of these characteristics are described by Horton and Strahler and his associates. The latest comprehensive works and reviews of Moriwasa (1959) and Scheidegger (1961) list the symbols and description of drainage basins characteristics.

The terrain factors used in this investigation were selected from the long list of basin morphometric properties.

Stream Order

As suggested by Strahler (1952) stream order is the assigned level of magnitude of stream segments in the drainage network of a watershed. The smallest tributaries are designated as first order; two first order stream units may form a second order stream segment or may be joined by additional first order segments without increasing the stream order. The major stream of the basin represent the highest order.

Bifurcation Ratio

Bifurcation ratio is the ratio between the number of stream segments of a given order and the number of stream segments of the next higher order. Scheidegger (1961) stated that these ratios are constant except where strong geological control is present. Typical first to second order ratios are 4 to 5, second to third order, 3 to 5.

Basin Area

This refer to the area of the entire drainage basin which contribute runoff to the stream segment of certain order down to its lower end. When measured from topographic maps by use of a planimeter, basin area represent the horizontal projected area rather than the actual surface area.

Basin Length

Basin length is the longest dimension of a drainage basin, usually measured from the mouth of the basin.

Stream Length

Stream length is the average length of stream segments of a given stream order.

Total Stream Length

It is the cumulative total of lengths of all stream segments of all orders in the watershed.

Drainage Density

Drainage density is the ratio of the total stream length of all segments in a basin to the total area of the basin, measured in the same units; that is, drainage density may have a dimension of miles per square mile, meters per square meter, etc. Horton (1945) gives an example of drainage density of 2.74 miles per square mile for a poorly drained area, and 0.74 miles per square mile for a well drained area.

Stream Frequency

Stream frequency or stream density is the number of stream segments of a given stream order per unit area of the drainage basin.

Constant of Channel Maintenance

Schumm (1956) proposed this term as the watershed area necessary to support one unit length of drainage channel, or merely the reciprocal of the drainage density.

Channel Gradient

Channel gradient is the tangent of the vertical angle of the stream. Morisawa (1959) used both the field measurement of the vertical angle at the point of measurement and a map measurement of the ratio of the total fall from head to mouth over the longest length.

Texture Ratio

Smith (1958) defined texture ratio as the number of crenulations on the contour having the maximum number of such crenulations within a given drainage basin divided by the perimeter of the drainage basin, or simply the number of crenulations or number of stream crossing per unit length of traverses drawn on topographic map.

Basin Relief

Basin relief is the difference in elevation between the highest and lowest points in a drainage basin.

Local Relief

Local relief according to Peltier (1955) is the maximum relief per unit area.

Average Elevation

Wood and Snell (1960) defined average elevation as the mean elevation of a drainage basin calculated from a number of random points.

Ruggedness Number

Melton (1957) introduced the term "ruggedness number" as dimensionless number to make geometric similarity comparison. It is the product of drainage density and relief both expressed in similar unit.

Roughness

Peltier (1955) used "roughness" as the number of discrete hilltops and/or peaks per square mile.

Mean Valley Depth

This is the average depth of the valley along one stream segment. Pike (1961) estimated mean valley depth on topographic map using the relationship:

$$MVD = \frac{I \times N}{S_c}$$

where MVD = mean valley depth

I = contour interval

N = number of contour crossings per unit of traverse

S_c= number of slope direction change per unit of traverse

Basin Shape Factor

Several factors have been proposed to quantify basin shapes, but the most commonly used is the "circularity factor" which is equivalent to the ratio of the area of drainage basin to the area of a circle having the same perimeter as the basin.

Stream Junction Angle

Stream junction angle is the junction or axil angle between two joining streams. Horton (1945) defined it as:

$$\text{Cos } Z = \frac{\tan S_b}{\tan S_g}$$

where S_b = channel slope of the major stream

S_g = resultant ground slope which is also equal to the slope of tributary stream

Length of Overland Flow

Horton (1945) defined this as the length of flow over the ground surface from the drainage divide until the runoff becomes concentrated in definite stream channels.

Inflection Angle of Contour Lines

Melton (1957) proposed this drainage basin characteristic as the angle which a contour line makes with itself where it depicts a channel.

MATERIALS AND METHODS

Materials

Soil Maps

Soil Association Map of Kauai. Soil association maps were available for most of the islands of Hawaii State. These maps were prepared by the Soil Conservation Service (SCS), USDA, by grouping soil series which occur in close geographic association over relatively wide areas. A given soil association includes two or more dominant soil series which developed from similar parent material having similar drainage condition and occur on the same general topographic location.

Soil association is most commonly used in reconnaissance soil surveys by SCS. The basis of soil association includes among others, topography, natural drainage, parent material which can be directly or indirectly seen on aerial photographs or inferred from topographic maps of the area.

A soil association map of Kauai was made available by SCS for use in this study. There were ten soil association areas established and mapped on this island:

1. Areas dominated by Jaucas-Mokuleia soils: Deep, excessively drained, sandy and moderately fine textured, nearly level to gently sloping soils along the coast.
2. Areas dominated by Hanalei-Kaloko-Pakala soils: Deep, well to poorly drained, medium and fine textured, nearly level soils on floodplains and bottomlands.

3. Areas dominated by Kekaha-Nohili soils: Deep, well to poorly drained, medium and very fine textured soils developed in alluvium on nearly level coastal plains.
4. Areas dominated by Kapaa-Pooku-Halii-Makapili soils: Deep, well to moderately well drained, fine textured soils high in aluminum and iron oxides on nearly level to steep uplands.
5. Areas dominated by Lihue-Puhi soils: Deep, well drained, moderately fine and fine textured soils developed in materials weathered from basic igneous rock on gently sloping to steep uplands.
6. Areas dominated by Makaweli-Waiawa-Niu soils: Deep and shallow, well drained, moderately fine and very fine textured soils developed on materials weathered from basic igneous rock on gently sloping to steep uplands.
7. Areas dominated by Waikoma-Kalihi-Koloa soils: Shallow to deep, moderately fine and very fine textured soils developed in material weathered from basic igneous rock and alluvium on gently sloping uplands and nearly level bottomlands.
8. Areas dominated by Mahana-Kokee-Paaiki soils: Deep to moderately deep, medium and fine textured soils developed in materials weathered from volcanic ash and basic igneous rock on moderately sloping to very steep uplands.
9. Areas dominated by Waialeale-Alakai soils: Shallow to deep, somewhat poorly to very poorly drained mineral and organic soils on nearly level to very steep uplands.

10. Areas dominated by rough mountainous land: Rough broken land, rock outcrop--well to excessively drained, very steep to precipitous lands of the mountains and gulches.

Great Soil Group Map. The great soil group is one of the categories of the new comprehensive soil classification system (Soil Survey Staff, 1960). The categories of the system, from the highest level are: Order, suborder, great group, subgroup, family and series. Soil type is the mapping unit and it is not a member of the classification, but it is a practical unit shown on a map. Classes of soils are built up by grouping the mapping units into successively higher and higher categories on the basis of similarity. The great soil group map prepared by SCS is a result of grouping soil types into soil series and soil series into great soil group on the basis of kind and arrangement of diagnostic horizons. Each great group is considered to be uniform with respect to the kind and arrangement of diagnostic horizons and features and to exist in a relatively narrow range of climate.

The great soil group map used in this study is still tentative because of the modifications suggested by SCS in placing certain soil series in one or another great group. Nevertheless, the map was used in this investigation to determine whether or not the quantitative terrain data collected for a certain great soil group area are statistically different from the data obtained for other great group areas.

There are eighteen great soil groups established for the island of Oahu. The unpublished, tentative map prepared by SCS showed the following great soil groups:

1. Ustipsamments--This great group belongs to the Order Entisols, recent soils and soils on very steep slopes. Ustipsamments are characterized by a sandy texture in dry, hot climatic areas.
2. Chromusterts--These soils are Vertisols and/or tropical Black Earths and other dark, clayey, swelling soils. They have high chroma and are developed in dry, hot climatic areas.
3. Pellusterts--These soils are Vertisols possessing low chroma and are developed in dry, hot climatic areas.
4. Pelluderts--The Pelluderts are also with low chroma Vertisols but are developed in humid climates.
5. Dystrandepts--These soils belong to the Order Inceptisols, soils not usually dry with weakly-developed horizons. Dystrandepts are volcanic ash soils with low base saturation.
6. Dystropepts--Inceptisols with low base saturation.
7. Eutrandepts--Eutrandepts are also volcanic ash soils but with high base saturation.
8. Eutropepts--Inceptisols in the tropics with high base saturation.
9. Ustropepts--Inceptisols in dry, hot tropical areas.

10. Humitropepts--Inceptisols in the tropics with high humus content.
11. Tropaquepts--Wet tropical Inceptisols.
12. Rendolls--These soils are members of the Order Mollisols, grassland soils in subhumid regions with deep, dark well-structured surface soils. Rendolls are calcareous Mollisols, with horizons containing more than 40 percent $CaCO_3$ below the solum.
13. Rhodustalfs--This great soil group is a member of the Order Alfisols, timbered soils other than Podzols of subhumid regions. Rhodustalfs are dark-red Alfisols in dry, hot climates.
14. Tropohumults--These soils belong to the Order Ultisols, timbered soils other than Podzols of humid regions. Tropohumults are Ultisols in the tropics containing relatively high amount of humus in the upper part of argillic horizon.
15. Haplustoxs--This great soil group is a member of Order Oxisols, a very strongly weathered soils or soils developed on very old tropical landscapes. Haplustoxs are normal oxisols in dry, hot climates.
16. Eutrorthoxs--Oxisols high in base saturation.
17. Gibbsihumoxs--Oxisols high in gibbsite and occurring in the humid regions.
18. Troposaprists--Troposaprists are highly decomposed Histosols in the tropics.

Other parts of Oahu not classified under any one of the above 18 great soil groups are classified as Miscellaneous Land Types.

Topographic Map

Topographic maps were used to obtain quantitative measurements of several terrain factors considered in this paper. The accuracy of these maps, therefore, were carefully checked before the work was started.

The topographic maps (1:24,000) issued by the U.S. Geological Survey (USGS) provided a very convenient scale for much of the quantitative analysis of various terrain factors such as average elevation, local relief, average slope and slope curvature. One of the great merits of this map is its 40-foot contour interval because this gives a very good indication of the shape of the ground and is very suitable for most measurement techniques.

The major considerations in collecting the quantitative terrain data from topographic maps are map reliability, map scale, operator's training and experience, sampling units and class intervals for the values collected.

The early U.S. topographic maps cannot be used for quantitative terrain analysis because contour lines on these maps were highly generalized and slopes were not shown correctly.

Salisbury and La Valle (1963) studied the errors involved in the use of maps of different scales. They used three scales, 1:24,000, 1:62,500 and 1:250,000 and measured local relief, slope inclination and slope width and found that with decrease in scale, errors result from the increasing generalization of contour lines, increasing contour interval and increasing operator's error.

Strahler (1956) studied the operator's variance in slope measurements on the 1:24,000 USGS topographic map by means of t-test of paired differences of slope values read by two operators at the same point. The test gave a very low mean differences, not significantly different from zero. Hammond (1954) checked the operator's variance in the study of slope inclination on the 7.5-minute quadrangle, 1:24,000 USGS topographic map. He found that 60 percent of the estimates of two inexperienced operators coincided, 37 percent differed by one slope class and only 3 percent by two classes. These studies suggest that with some training several operators can obtain very similar results for the same type of terrain using 1:24,000 topographic maps published by USGS.

Aerial Photographs

It is not possible to examine physically every piece of terrain as it exists naturally. Aerial photographs taken at a suitable scale provide a pictural image of a terrain at manageable size and when viewed stereoscopically produces a three-dimensional image of the terrain which can be completely examined and measured for some quantitative data.

Panchromatic, black and white, vertical aerial photographs purchased from ASCS, USDA were used in this study. The photographs were taken in 1965 at an altitude of 12,000 feet using a 6-inch focal length aerial camera producing photo scale ranging from 1:24,000 to 1:26,000 depending on the elevation of the land.

No interpretation of aerial photographs for soil study was made; hence, aerial photographs were utilized mainly for collecting quantitative data for certain terrain factors used in this paper. In using aerial photographs, however, several conditions were considered:

1. Aerial photograph is not a planimetric map where all the features are plotted in their exact position. Aerial photograph is equivalent to map only if the photography is truly vertical and the object is absolutely a horizontal plane.
2. Aerial photograph do not have uniform scale throughout the entire coverage since it is taken from one position only.
3. Since aerial photograph is taken from one position directly over the center of the area, object not at the exact center are displaced to a greater or lesser degree depending on their elevation and the distance from the center. An object such as a lighthouse when directly underneath the camera will appear to have the top directly above the bottom, but if the same lighthouse is at one side of the photograph the top will be displaced and appear to be farther from the center of the photograph than the bottom of the lighthouse.
4. The greater the elevation change above or below the datum plane the greater is the displacement. However, at the center of the photograph there is no such displacement regardless of the distance from the camera or the height of the object.

The basic geometric properties of vertical aerial photographs are fully discussed in many textbooks of photogrammetry and photo interpretation. The Manual of Photographic Interpretation published by American Society of Photogrammetry (1961) has brief discussion of the subject on the point of view of photo interpreter.

Equipment

Lens Stereoscope. The lens stereoscope (Figure 1) provides a simulation of distance vision and enables the observer to view two images of the same object recorded from different point in space and thus perceive the object in three dimensions. The distance between the lenses is adjustable in order to accommodate eyes with different interpupillary distance.

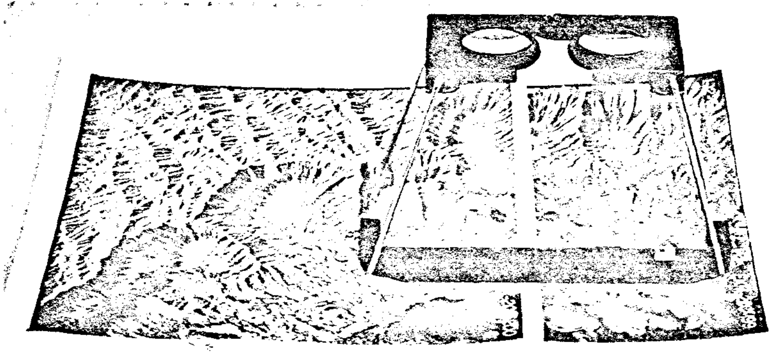


FIG. 1. LENS STEREOSCOPE WITH PARALLAX BAR ATTACHED TO THE LEGS.

The advantages of lens stereoscope over other types of stereoscopes are its small size, portability, higher manification and low cost. One disadvantage, however, is the restricted field of view that it provides. The observer cannot view the entire stereoscopic area in the flight line without raising the edge of the photographs.

Mirror Stereoscope. In mirror stereoscope (Figure 2) a combination of prisms and mirrors separate the lines of sight from each of the observer's eyes. The distance between the mirrors is much greater than that between the eyepieces so that a three-dimensional image can be received from a pair of photographs laid side by side without overlapping each other. The distance between the eyepieces of mirror stereoscope is usually adjustable to fit the interpupillary distance of human eyes. The advantages of mirror stereoscope over lends stereoscope are: (1) the observer can view all or most of the stereoscopic area of a pair of photographs without raising or shifting the photographs or moving the stereoscope, and (2) he can conveniently use measuring instrument under the stereoscope. The disadvantages of

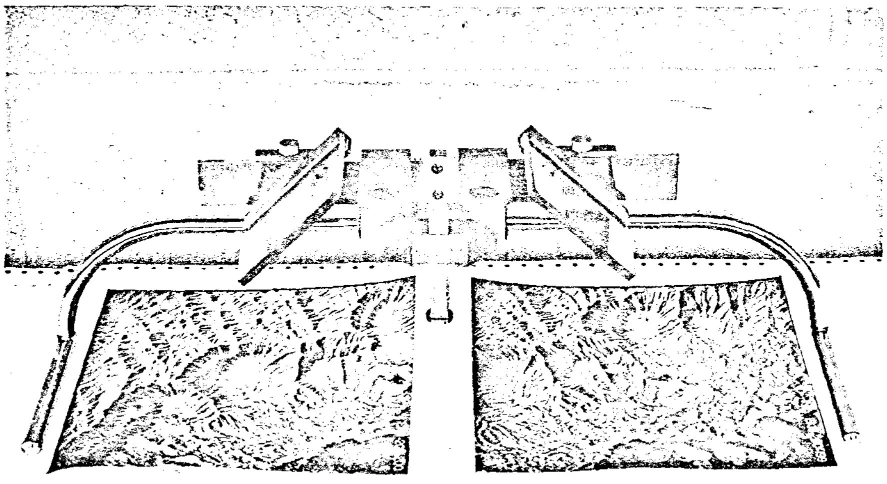


FIG. 2. MIRROR STEREOSCOPE OVER A PAIR OF STEREOSCOPIC AERIAL PHOTOGRAPHS

the mirror stereoscope are its large size, the necessity of a special viewing position and high cost.

Parallax Bar. The parallax bar (Figure 3) is used to determine heights of objects on stereoscopic pairs of vertical aerial photographs by the floating dot principle and to determine the slope of the land and depth of gullies. The main parts are a bar, which may be attached to the legs of a lens stereoscope (Figure 1), two transparent plates, each with a small dot in the center and a finely graduated micrometer device which measure the movement of one dot in relation to the other. The bar is operated by attaching it to the legs of a stereoscope which rests over a properly oriented pair of stereoscopic photographs. The two dots are made to appear as one by adjusting the micrometer.

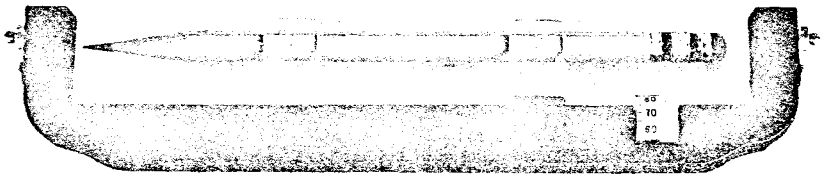


FIG. 3. PARALLAX BAR, MODEL HF-2

The particular parallax bar described in this paper was a Model HF-2 Height Finder distributed by Abrams Instrument Corporation, Ann Arbor, Michigan.

Vertical Sketchmaster. A vertical sketchmaster (Figure 4) transfers detail from aerial photographs to a map sheet, or from one drawing or map to another. The operator looks through a half-silvered, semi-transparent mirror mounted at the front. The mirror reflects light but also permits light to pass through, enabling the operator to see the image of the photograph and the map manuscript superimposed on its surfaces. The image is reflected into upright position by a large opaque mirror and the legs are adjusted to correct for tilt and differences in scale.

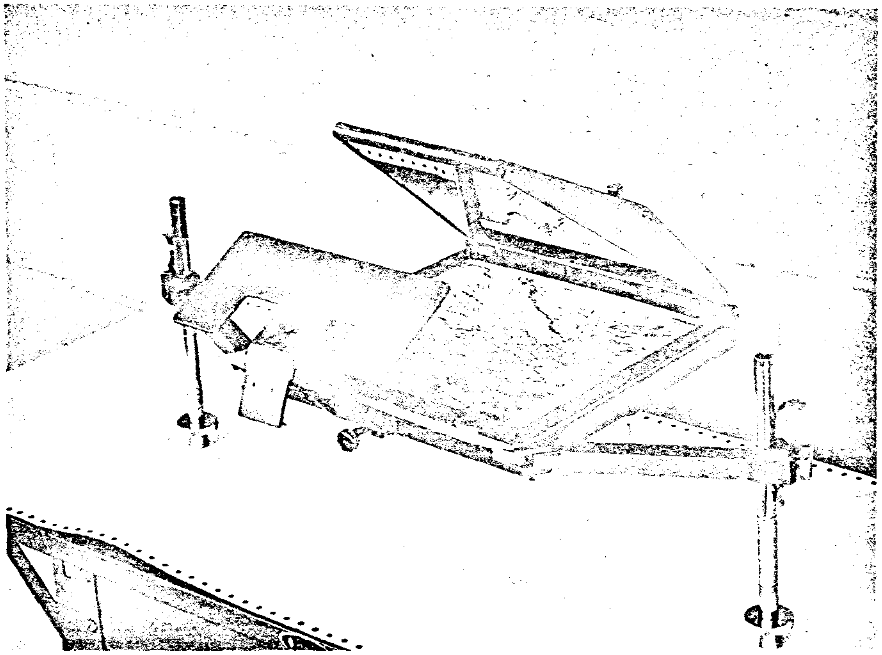


FIG. 4. VERTICAL SKETCHMASTER

The vertical sketchmaster was used in this study mainly to transfer the details drawn on aerial photographs to topographic maps.

The use of this instrument is discussed in detailed in the instruction manual furnished by the manufacturer, Keuffel and Esser Company.

Methods

General

The development of the testing procedures used in this study involved considerable amount of trial and error, incorporation of work of others, and a small degree of invention.

The basic procedures used in measuring the terrain factors on the aerial photographs were adapted from manuals published by the Society of American Photogrammetrist (1960, 1966). Modifications of some techniques to suit the topography of the study area were made through trial and error supplemented with reasonable amount of field verifications. Measurements made on topographic maps were based on the work of many geomorphologists and geographers on morphometric analysis.

The parallax bar or the HF-2 Height Finder was used to obtain the basic terrain data such as differences in elevation, height of an object and slope of the land from aerial photographs. In order to determine the accuracy of this equipment the data obtained from aerial photographs were statistically compared with the data obtained by conventional field methods. The aerial photographic procedure was adapted only when the difference between the two methods was statistically not significant.

The islands of Oahu and Kauai were selected as study areas. The availability of complete sets of aerial photographs, topographic maps and soil maps and time were the reasons for the choice of these islands. Proximity and convenience of undertaking the field work were also reasons for selecting Oahu as a study site.

The actual testing program consisted of five steps:

1. Selection of soil units
2. Selection of observation units
3. Selection of terrain parameters
4. Procedures of measurements of terrain parameters
5. Application of data processing and statistical analysis

Selection of Soil Units on Oahu

There were 18 great soil groups established and mapped by SCS on Oahu. However, only eight of these great groups contained sufficient number of 0.5-mile square test cells to be included in the analysis of terrain factors in relation to the boundaries drawn in the map. Numerous urban areas and man-made features reduced the number of cells considerably.

The nine great soil groups, their symbols, the acreage and the number of test cells in each soil area are shown in Table I. The acreage is the approximate total of the great soil group on the whole island based on the acreages of the soil series belonging to the particular great soil group.

The distribution of the test cells in each of the great soil group areas studied is shown in Figure 5.

Detailed morphological description of the soil series members of the great soil groups are published by the U.S. National Cooperative Soil Survey (1966). It was not the purpose of this paper to examine closely in the field all of the member soil series

TABLE I. GREAT SOIL GROUPS SELECTED ON OAHU FOR TERRAIN MEASUREMENTS, WITH SYMBOLS, ACREAGES AND NUMBER OF TEST CELLS

Great Soil Group	Symbol	Acreage	Number of Test Cells
Tropohumults	TH	46,727	44
Haplustoxs	HU	28,125	21
Gibbsihumoxs	GH	10,000	24
Eutrorthoxs	EO	21,400	20
Rhodustalfs	RU	6,900	18
Dystrandepts	DA	3,350	13
Humitropepts	HT	11,222	7
Ustropepts	UT	3,500	6
		Total Number of Cells	153

FIG. 5. TEST CELLS DISTRIBUTION AMONG THE GREAT SOIL GROUP AREAS ON OAHU (FOR THE SYMBOLS AND NUMBER OF THE TEST CELL, SEE TABLE I)

of each of the great group studied. The boundaries separating each great soil group were assumed to represent the true distribution of soils in the field and no verification was made in this study.

The general field characteristics of the great soil group presented in this paper were summarized from the morphological description of the member soil series published by the U.S. National Cooperative Soil Survey.

Tropohumults (TH). The soil members of the great group Tropohumults have dark brown to dark reddish brown silty clay A horizon with thickness ranging from 6 to 17 inches. This A horizon has a strongly developed, fine to very fine subangular blocky structure. The B horizon has a total thickness ranging from 29 to 70 inches consisting of reddish brown to dusky red silty clay with moderately developed fine to very fine subangular blocky structure. This horizon is subdivided into 4 to 5 layers varying slightly in color, texture, consistency and amount of clay films on ped faces. The soils have developed in alluvium and residuum weathered from basalt.

Much of the Tropohumults on Oahu is in pasture generally on gently to steeply sloping alluvial fans and terraces on the western and eastern slope of the Koolau Range at elevations ranging from 1,000 to 1,700 feet above sea level.

Haplustoxs (HU). Typically, the soil members of the Haplustoxs have dark reddish brown, friable silty clay loam to silty clay A_{p1} horizon which has a weakly developed granular structure. The underlying A_{p2} horizon is a dark reddish brown to dark red, slightly hard silty clay with weakly developed medium and coarse subangular blocky structure. The A horizon has a total thickness ranging from 12 to 18 inches. The B horizon is dusky red to dark reddish brown silty clay loam to silty clay that have moderately developed fine subangular blocky structure with thickness ranging from 3 to 5 feet. It is generally subdivided into 3 to 4 layers which differ slightly in color, texture and structure. The soil has formed in residuum and alluvium from basic igneous rock.

Much of the Haplustox has topographic conditions favorable for the production of sugar cane and pineapple. The largest body of Haplustox is found on the southern slope of Schofield Plateau (Figure 5). However, no test cell was set in this area because of high intensity of urban use.

<u>Gibbsihumoxs (GH)</u>. The soil members of the Gibbsihumoxs have dark yellowish brown to dark grayish brown silty clay loam to silty clay A horizon containing few gravel size angular gibbsite aggregates. It has a thickness ranging from 3 to 8 inches. The B horizon consists of 2 to 4 feet of yellowish red to reddish brown silty clay loam with weakly developed fine subangular blocky structure. The lower portion of the B horizon contains considerable amounts of yellowish red and reddish brown moderately weathered gravels impregnated with materials containing more than 30 percent gibbsite. The regolith of Gibbsihumox soil members is residual from basalt.

Gibbsihumoxs occur on moderately to steeply sloping, dissected uplands on the northeastern slope of Koolau Range at elevations ranging from 300 to 1,000 feet above sea level (Figure 5). This is the only body of Gibbsihumoxs on Oahu. Much of the area is not cultivated due to unfavorable topographic condition.

Eutrorthoxs (EO). The soils belonging to Eutrorthoxs have dark reddish brown to dusky red, friable granular silty clay A_p horizon with thickness of 6 to 15 inches. The B horizon is 3 to 5 feet and consists of dark reddish brown to dark red moderately developed silty clay. The upper B horizon is usually hard and compact and has strongly developed subangular blocky structure. The soils have developed in residuum and alluvium from basalt.

Major portions of Eutrorthoxs are devoted to the production of pineapple. These soils occur on relatively undissected upland in the Schofield Plateau with slope ranging from 0 to 25 percent (Figure 5).

Rhodustalfs (RU). The soil members of the Rhodustalfs generally have a dusky red or dark reddish brown, 4 to 12 inches, moderately to strongly developed granular silty clay A_p horizon. The B horizon is dark red, has moderate and strong structural grades and silty clay texture. The regolith of the soil members of the Rhodustalfs consists of materials weathered from basalt.

Rhodustalfs occur on rolling to very steep upland with slopes of 12 to 70 percent but dominated by slope over 30 percent. The area is mostly in pasture and brushes and scrub on the northern end of the Waianae Range (Figure 5). Vegetation consist mainly of guava (Psidium guajava), lantana (Lantana camara), pilipiliiula (Chrysopogon aciculatus) and bermuda grass (Cynodon dactylon).

Dystrandepts (DA). Soils classified as Dystrandepts generally have dark reddish brown, relatively thick (7 to 18 inches) granular silty clay A_1 horizon. The B horizon is dark red, friable silty clay, having a weakly developed fine subangular blocky structure. It has a thickness ranging from 25 to 50 inches. Underlying the B horizon is the C horizon composed of dark reddish brown silty clay loam with few to many black unweathered pebble-size cinders. Members of the Dystrandepts have developed from volcanic ash and they are usually underlain by andesite or basalt rocks.

Dystrandepts occur on gently sloping to steep, dissected uplands on the easternmost point of Oahu, southwestern slope of Waianae Range and in the Tantalus area, at elevations ranging from 1,000 to 2,000 feet above sea level (Figure 5).

Humitropepts (HT). Humitropepts generally have dark reddish brown, friable silty clay loam A_p horizon with thickness ranging from 6 to 12 inches and with a weakly granular structure. The B horizon is dark reddish brown, slightly hard silty clay loam having moderately developed, fine and medium subangular structure with thickness ranging from 20 to 40 inches. They have developed in old gravelly alluvium mixed with volcanic ash.

Humitropepts generally occur on gently sloping to moderately steep uplands on the western and northeastern slopes of the Waianae Range at elevations ranging from 200 to 2,000 feet (Figure 5). Greater portion of this great graou area is devoted to the production of pineapple and sugar cane.

Ustropepts (UT). Soil members of Ustropepts generally have dark reddish brown, friable granular silty clay loam A_1 horizon overlying a reddish brown, silty clay loam B horizon having a moderately strong subangular blocky structure. The thickness of the solum ranges from 4 to 5 feet.

Ustropepts occur in many parts of Oahu at elevations ranging from sea level to 2,100 feet above. However, the only area studied was the area occurring on the western slope of Waianae Range (Figure 5). Greater portion of the Ustropept areas is built-up areas.

Selection of Soil Units on Kauai

There were six soil associations selected on Kauai for terrain measurements. The choice of these areas was mainly based on the extent of coverage and the sufficient number of test cells which could be studied.

Table II shows the soil associations, their symbols, acreage and number of test cells.

The distribution of the test cells in each of the soil association areas are shown in Figure 6.

Kapaa-Pooku-Halii-Makapili Soils (KP). This soil association consists primarily of deep (48 to 60 inch solum), moderately well to well drained fine textured soils. It is found only on the eastern half of Kauai on nearly level to steep uplands with elevation ranging from 100 to 1,000 feet above sea level (Figure 6).

Examination of the 1965 aerial photographs showed that ohia lehua (*Metrosideros polymorpha*) was common at high elevation while guava (*Psidium guajava*) and lantana (*Lantana camara*) as well as

TABLE II. SOIL ASSOCIATIONS STUDIED ON KAUAI, WITH SYMBOLS ACREAGES AND NUMBER OF TEST CELLS

Soil Association	Symbol	Acreage	Number of Test Cells
Kapaa-Pooku-Halii-Makapili	KP	34,240	30
Lihue-Puhi	LP	36,480	25
Makaweli-Waiawa-Niu	MW	29,440	35
Waikoma-Kalihi-Koloa	WK	7,040	14
Mahana-Kokee-Paaiki	MK	12,720	45
Waialeale-Alakai	WA	11,200	20
	Total Number of Cells		169

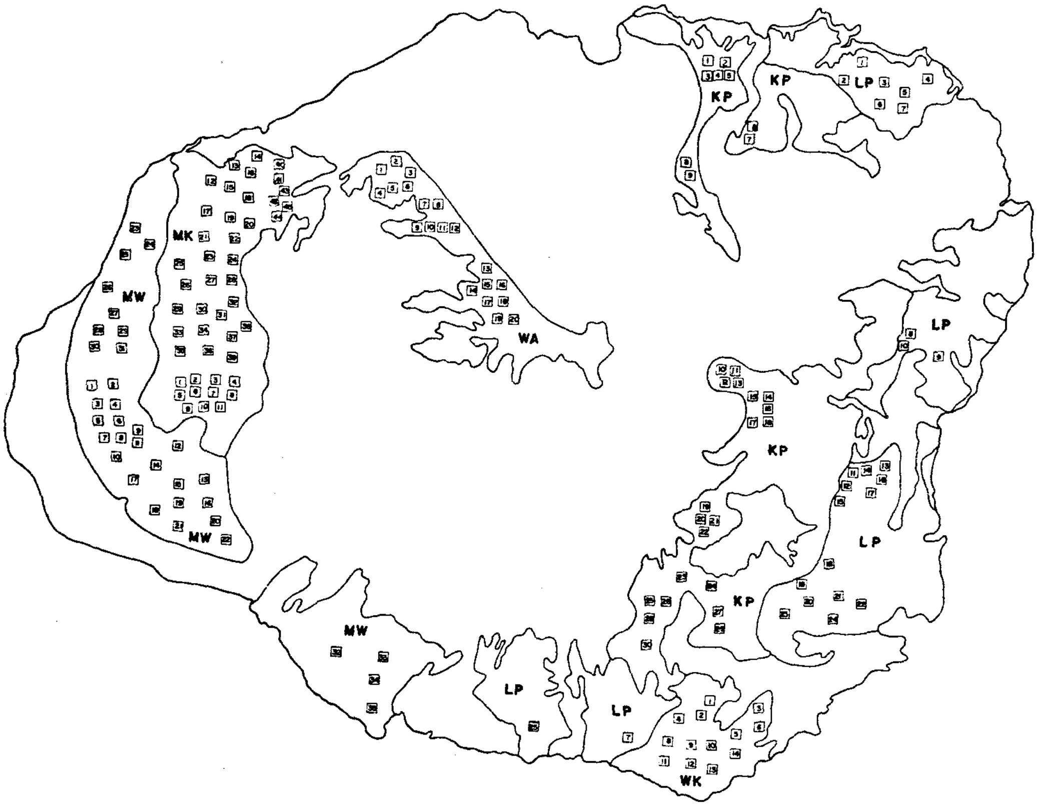


FIG. 6. TEST CELL DISTRIBUTION AMONG THE SOIL ASSOCIATION AREAS ON KAUAI (FOR THE SYMBOLS AND NUMBER OF THE TEST CELL, SEE TABLE I)

pasture occupy the intermediate uplands. Few candle nut trees (Aleurites moluccana) were observed in the gully floor. The cultivated portion of this soil association area is utilized for sugar cane production.

Lihue-Puhi Soils (LP). Areas dominated by the Lihue-Puhi soils generally have deep (60 inch solum), well drained, fine textured soils that developed in materials weathered from basic igneous rock. They occur on nearly level to steep upland with slopes ranging from 8 to 14 percent primarily on the eastern coast of Kauai at elevations extending from sea level to 800 feet above the former. It is an area of maximum urban development. The cultivated area is mainly utilized for sugar cane and pineapple production. The vegetation in non-agricultural areas consists primarily of lantana and guava scrubs and grasses.

Makaweli-Waiawa-Niu Soils (MW). This association consists of deep and shallow (8 to 60 inch solum) well drained, moderately fine and very fine textured soils developed in materials weathered from basic igneous rock, on gently sloping to very steep uplands (7 to 50 percent slope). They occur on the western part of Kauai island at elevations ranging from sea level to 2,000 feet above. The vegetative cover consists mainly of koa haole (Leucaena leucocephala) grasses and keawe trees (Prosopis pallida) along alluvial flats and gullies. Sugar cane dominates the cultivated areas.

Waikoma-Kalihi Soils (WK). This association occurs as small areas on the southernmost point of Kauai at elevations ranging from sea level to 360 feet above the former. Table II shows that these soils occupy only an area of approximately 7,040 acres. They are shallow to deep (16 to 60 inch solum), moderately fine and very fine textured soils developed in materials weathered from basic igneous rock and alluvium on gently sloping uplands (1 to 8 percent slope) and nearly level bottomlands. Koa hoale and pasture grass are the dominant cover of the uncultivated portion while sugar cane is the main crop of the cultivated areas.

Mahana-Kokee-Paaiki Soils (MK). The Mahana-Kokee-Paaiki soils occur only on the western portion of Kauai at elevations ranging from 2,900 to 4,200 feet above sea level. This association consists of moderately deep to deep (30 to 60 inch solum), medium and fine textured soils developed in materials weathered from volcanic ash and basic igneous rock on moderately sloping to very steep uplands having a slope of 20 to 35 percent.

Koa (Acacia koa) and ohia lehua dominate the forest area with scattered candle nut trees in the gully bottom. Lantana and grasses were observed in many uncultivated and unforested portion. Sugar cane is grown in the cultivated area.

Waialeale-Alakai Soils (WA). This soil association occurs in the Alakai Swamp at elevations ranging from 3,000 to 5,000 feet above sea level. It consists of shallow to deep (30 to 60 inch solum), somewhat poorly to very poorly drained mineral and organic soils on nearly level to very steep uplands with slope of 15 to 40 percent. Although the area is known to be wet and swampy, analysis of aerial photographs revealed that greater portion of the swamp is highly dissected, an indication of good external drainage. The flat to gently sloping area has peaty surface soil and supports low growth of ohia lehua. Wildlife is the only use of the area.

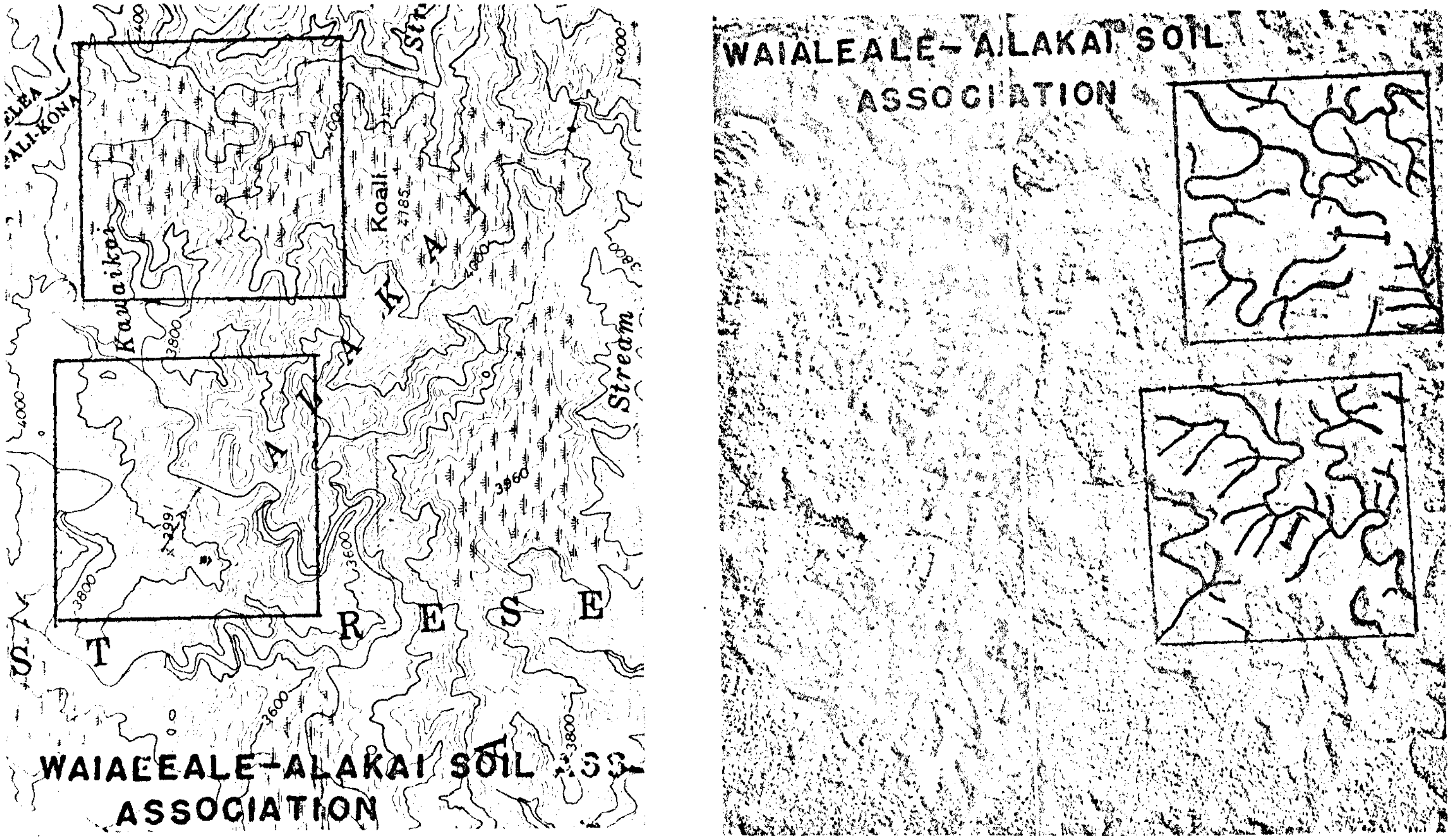
Selection of Observation Units on Oahu and Kauai

Location. After the decision was made to confine the study to a definite number of great soil groups and soil associations, selection of the location of the individual observation units or test cells was carefully considered.

The locations of the test cells were based on soil maps furnished by SCS without being biased by the appearance of the topographic maps. The exact location of every test cell drawn on the soil map was transferred onto the topographic map and aerial photograph of the area to measure terrain factors (Figure 7).

There were instances when the test cell was shifted after examining the aerial photographs, because the test cell occurred on cultural features, large body of water, airports or subdivision which gave meaningless measurements.

An attempt was made to have the test cell include only a single homogenous soil association or great group as indicated by the soil maps although the detailed pedologic soil maps might well indicate the minor inclusions of other soils not associated with the soil unit mapped. Although the test cells were distributed at random within each soil association or great soil group,



Topographic Map

Aerial Photo Stereogram

FIG. 7. TWO OF THE TEST CELLS IN ONE OF THE SELECTED SOIL ASSOCIATIONS ON KAUAI. CELLS WERE LOCATED ON SOIL MAP AND THEN TRANSFERRED TO TOPOGRAPHIC MAP AND AERIAL PHOTOGRAPHS. FOR DEPTH EFFECT, USE POCKET STEREOSCOPE IN VIEWING THE AERIAL PHOTOGRAPH.

considerable care was taken to locate them as far as possible from the boundaries to reduce the border effect.

Size and Shape of Test Cell. The problem of the size and shape of the sampling unit necessary for quantitative terrain analysis is a complex one. Two types of unit have been used: (1) irregular areas delimited subjectively on the basis of selected terrain characteristic, such as drainage basin, and (2) uniform geometric units. Based on the studies made by Raisz and Henry (1937) in New England, Thoman (1952) and Calef and Newcomb (1953) in Illinois, it is known that a grid of uniform sampling or determination unit has an advantage over one of irregular unit such as drainage basin because it is applied systematically throughout the whole area of study and it avoids the subjectivity involved in the drawing of individual boundaries. Its weaknesses are the unavoidable relocation of some terrain boundaries and the subjective decision involved in the choice of the size and shape of these units.

A one-half mile square (160 acres) test cell was selected as the unit cell in this study. The selection of the size of the test cell was based on practical considerations and on Wood and Snell (1960) rational method of selection of a test cell size. Basically, the method consists of determining the maximum differential relief (highest elevation minus lowest elevation) within a series of successively larger diameter concentric sample cells. When various differential reliefs were plotted against the increasing diameter of the sample cell, a flattening or knickpoint was found. This knickpoint corresponds to the proper diameter of a sample unit which is large enough to show an area tendency but not so large as to be masked by regional factors.

Detailed steps followed in determining test cell size were:

1. Twenty-seven points were selected at random on topographic maps of Oahu. Similarly, 25 points were selected on Kauai.
2. A transparent template consisting of series of concentric circles and having diameter increments of one-half mile was prepared.
3. The template was laid over every point and the relief for each circle was determined by getting the difference between the highest and lowest elevation within each circle.
4. Values were then plotted on a graph paper with relief on the vertical axis and length of diameter increments on the horizontal axis and points were connected.
5. A knickpoint occurs on the line representing increase of relief with size of area and from that point the line moves upward slowly. Figure 8 shows that the knickpoint occurs at the one-mile diameter (one-half mile radius). Thus, the analysis indicated that a half-mile square should be used as cell size or if circular shape is used, a one-half mile radius cell should be utilized.

From practical standpoint, a half-mile square test cell was the most appropriate size. A much larger cell would have been very difficult to fit into the spotty pattern of soils mapped in the area and more inclusions of soil series not belonging to the selected soil association and great soil group. For similar

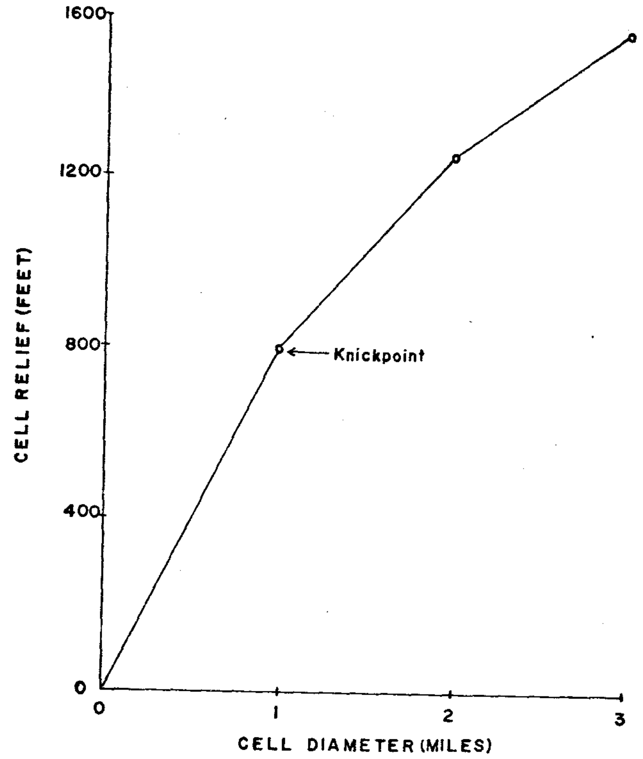


FIG. 8. GRAPH SHOWING KNICKPOINT BASED ON MEANS FROM 27 POINTS ON OAHU AND 25 POINTS ON KAUAI

reasons a circular cell was not selected because a one-mile diameter cell would be very large for the size of soil area on Oahu and Kauai.

Equal sized cells were chosen rather than irregularly sized sampling unit such as drainage basin, because it has been shown that the area of a drainage basin is one of the most important controlling factors of the basin. Other parameters associated with the drainage basin are usually very closely correlated with the area of the basin. By taking uniform areas, the variable of area is held constant and the true variation of the other parameters can be easily established.

Selection of Terrain Parameters

Terrain Parameters vs. Terrain Factors.

The term "terrain parameter" refers to the true or actual value of some terrain characteristics, while a "terrain factor" is the statistical estimate of that terrain parameter. The value of the terrain factor is the result of a sampling process in which a small number of measurements are used to estimate the actual value of the terrain characteristics which make the "population" of the terrain parameter. For example, the terrain parameter of average elevation is the true average elevation of an area, the average of the population of every point within the area. In this case, the terrain factor of average elevation is an estimate based on a sample consisting of a number of observations, the number of observations being less than the population. In this study the ten measurements of elevation of a sample were averaged to obtain the terrain factor "average elevation". Hence, this terrain factor was then an estimate of the population or actual value of the average elevation of the area.

Terrain Factors Selected.

A large number of terrain factors were described in a previous section. It was a major problem in this study to decide which of these factors could be used and might be significant in terms of mapping soils.

The decision to use the size and shape of test cells located in homogeneous soil units effectively eliminated the study of terrain factors based on an entire drainage basin such as stream order, bifurcation ratio, basin area, stream length, etc. However, this decision does not infer that this latter group of factors is not important. It only means that since this type of study was the first attempt to correlate the terrain factors and soil areas in Hawaii, the scope of the study allowed only the simple possible relationships to be investigated. It is quite possible that these drainage basin terrain factors might prove to be a fruitful area for further research.

One of the most important criteria used in the selection of the terrain factors was that they could be measured on aerial photographs and/or topographic maps. After careful consideration of the previous work on terrain quantification and the practical experience in mapping soils, ten terrain factors were selected in this study. Table III shows these terrain factors measured from each test cell for the eight great soil groups on Oahu and six soil associations on Kauai.

Transfer of Test Cells from Map to Aerial Photographs. A ruler and a soft pencil were about the only materials used in transferring the test cells from the topographic map to the aerial photographs. The cells which were selected at random on soil maps were properly identified and labeled before they were transferred on to topographic maps. From the topographic maps they were then transferred on to aerial photographs by visual examination of features that could be used as reference points. This transfer process required the development of sense of proportion. Some adjustments were made to compensate for variation in scale between the photographs and the map and distortion occurring on the outer borders of the photographs. In

TABLE III. TERRAIN FACTORS SELECTED FOR MEASUREMENTS ON OAHU AND KAUAI SOIL AREAS, WITH THEIR SYMBOLS AND UNITS OF MEASUREMENT

Terrain Factors	Symbol	Unit of Measurement
Average elevation	Ea	feet
Local relief	RL	feet
Average slope	Sm	percent
Mean slope Length	SL	feet
Mean slope length curvature	Slc	no unit
Mean slope width curvature	Swc	degree
Land texture ratio	TL	mile^{-1}
Drainage density	Dd	mile/square mile
Ruggedness number	Rn	feet/mile
Mean gully depth	Gd	feet

In cases of large relief displacement on aerial photographs, a vertical sketchmaster (Figure 4) was used to transfer the cell taking into consideration the scale difference. Therefore, there were cases where the perfect square cell on topographic map appeared as irregular-side cell on the photographs. However, the area of 160 acres remains constant and the feature within the cell are common to both map and photograph.

Comparisons of Three Methods of Terrain Slope Estimation

Slope of the land was one of the terrain factors selected for study. Before the decision was made as to what methods of terrain slope estimation should be used, a comparative study was made of three methods of obtaining slope data.

In soil survey and most land management studies, slope of the land is determined by means of the Abney hand level. The slope percent determined in the field is accurate for most land management inventories.

Another established method of estimating ground slope is with the use of topographic map since this map shows the elevation difference between any two points. Here, the slope is calculated by dividing the elevation difference by the horizontal distance between the same points. The accuracy of this method depends largely on the contour interval and scale of topographic map. High degree of accuracy is obtained on large-scale, small contour interval topographic map. In general, the scale and contour interval of the topographic map used in this study is satisfactory for the purpose with which the slope data will be used.

A third method of ground slope estimation is with the use of aerial photographs taking advantage of three dimensional image and the displacement of the position of an object with respect of a reference point. Several instrument such as the stereo slope meter, parallax bar and various floating line devices have been especially designed by various mapping and surveying agencies in the U.S. for measuring slope on aerial photographs. The principle and use of these instruments are adequately described in the Manual of Photogrammetry (1966).

Three methods of determining ground slope were compared to find out: (1) whether or not the estimates of slope percent obtained from measurement on contact prints of medium scale aerial photographs (1:24,000) using the parallax bar were as precise and accurate as the estimates made in the field with Abney hand level and (2) to compare the estimates from the aerial photographs with those obtained from 1:24,000 USGS topographic map.

Slope percent was calculated on topographic map by dividing the elevation difference between two points where slope was to be determined by the horizontal distance between the same points.

An HF-2 parallax bar attached to a pocket stereoscope was used to measure ground slope on aerial photographs (Figure 1). The use of this instrument is again discussed in detail in the Manual of Photogrammetry (1966) and many other textbooks of photogrammetry and photo interpretation. Slope percent is obtained from two measurements on aerial photographs--elevation difference and horizontal distance between two points. Elevation difference was determined by parallax measurements on stereo pairs of aerial photographs.

Parallax is the apparent displacement of the position of an object with respect to a reference point which is caused by a shift in the point of observation. Derivation of parallax equation and computation of parallax factor for pairs of aerial photographs are discussed in both the Manual of Photogrammetry (1966) and the Manual of Photographic Interpretation (1960).

Because of differences in field conditions and measurement techniques, five sites were selected for study. Base lines or traverses, approximately 100 feet long, were established at each site for slope percent estimation. Table IV shows the sites selected and the number of base lines established.

Average slope data for all sites using the three methods are presented in Table V.

The data in Table V indicate that in general the slope percent measured on the topographic maps or on the aerial photographs do not differ significantly from those obtained by ground measurements using the Abney level. In general, two factors tend to create higher standard errors on aerial photographic methods as steepness of slope increases. First, on a steep slope, it is usually more difficult to use the parallax bar because of difficulty of placing its floating circle precisely on the ground. Second, as the slope increases the image displacement, due to elevation differences, has a more pronounced effect on the length of base slope line.

Measurements made on every baseline on all sites indicated that slope percent estimated on aerial photographs were practically the same with that measured on the ground and on the topographic maps. One advantage of using aerial photographs is that the micro relief such as small landslides, small gullies, etc., which may be present along the established baseline can be observed. This is not possible on

TABLE IV. SITES SELECTED FOR STUDY OF THREE METHODS OF SLOPE MEASUREMENT AND THE NUMBER OF BASE LINES ESTABLISHED

Site	Number of Baseline
Roads	25
Forested hillslopes	25
Streams and drainageways	10
Sugar cane field	10
Pineapple field	10

TABLE V. AVERAGE SLOPE PERCENT AND STANDARD ERRORS OBTAINED BY THREE METHODS OF SLOPE ESTIMATION

Site	Topographic Map		Aerial Photo		Ground	
	Mean Slope	Standard Error	Mean Slope	Standard Error	Mean Slope	Standard Error
Roads	9.95	1.56	11.01	1.65	11.81	1.70
Forested hillslopes	31.48	2.43	34.31	2.55	34.44	2.50
Streams and drainageways	8.47	1.77	10.90	1.99	10.76	2.00
Sugar cane field	19.60	1.12	20.39	1.16	21.09	1.46
Pineapple field	5.26	0.29	5.89	0.26	6.71	0.27

topographic maps particularly if the contour interval is greater than ten feet.

Mechanics of Measurement of Terrain Factors

The terrain factors were measured after the test cells were transferred and properly labeled on both the topographic maps and the aerial photographs.

All values of terrain factors presented in this paper were collected within the test cells using both or either the USGS 1:24,000 topographic maps (40 feet contour interval) or the 1965 vertical black and white aerial photographs.

Average Elevation, Ea. Average elevation was determined on the topographic maps based on elevations of ten points established in the test cell. Elevation of each point was read directly on the map by means of contour lines. Elevation of points falling between the two contour lines were interpolated.

To facilitate the distribution of the ten points, a template was prepared by drawing grids on a transparent overlay dividing the cell into ten equal squares and placing a dot in the center of each grid. The template was laid over the cell drawn on topographic map, and the average elevation of the test cell was obtained after determining the elevation at each of the ten points.

Local Relief, RL. Local relief is the difference between the highest and lowest elevation in a test cell. It was estimated by reading the highest and the lowest elevations on the topographic maps.

Average Slope, Sm. Determination of average slope of the land in the cell was one of the major problems encountered in this study, particularly in dissected areas where the ground surface sloped in many direction and the length of slope was not uniform. Ideally, to estimate average slope, it is necessary to determine the ground slope of sufficient number of traverses established in all slope directions. The decision of selecting these traverses is very difficult and it is time-consuming. Locating the traverses in the cell is always biased by the general nature of topography. For this reason another method of determining the average slope of an area, that of Wentworth (1930), was sought. However, before employing the method, a study was made in which the average slope data obtained by the Wentworth method was compared with those obtained from aerial photographs based on measurements made on the ten test cells.

Table VI shows that the average slope of the land in the test cells is practically similar by the two methods. The time required by the aerial photo technique, however, was considerably greater than the Wentworth technique. Therefore, instead of using the HF-2 parallax bar (Figure 3) to estimate the average slope, the Wentworth method was used in all the test cells on both Oahu and Kauai.

For the actual slope of certain ground surfaces, aerial photographic technique is fast and just as accurate as field method. However, for estimating the average slope of an area as a whole the Wentworth method is more applicable since the problem of drawing the traverses are avoided.

TABLE VI. AVERAGE SLOPE OF TEN TEST CELLS OBTAINED BY THE WENTWORTH METHOD AND BY AERIAL PHOTOGRAPHIC TECHNIQUE AND THE TIME REQUIRED BY EACH METHOD

Test Cell	Average Slope (%)		Time Spent (Minute)	
	Wentworth Method	Aerial Photo Technique*	Wentworth Method	Aerial Photo Technique
TH-30	28.8	29.6	3	10
HU-1	3.6	3.9	1	4
GH-8	73.2	74.1	6	17
EO-3	11.3	10.9	2	7
RU-10	47.2	48.2	5	15
DA-11	16.9	17.3	3	9
HT-3	8.4	8.8	2	7
UT-6	13.3	12.8	2	9
TH-15	34.6	35.4	3	10
GH-9	55.0	56.1	5	15

*Based on ten observations. HF-2 parallax was used.

The steps used in determining average slope of the land (Wentworth's method) within every test cell were as follows:

1. A north-south, east-west grid of four lines were drawn on a transparent overlay with an area and dimension the same as the test cell.
2. The grid was laid over each of the cells, on north-south orientation (Figure 9a). All contour crossings were counted, tabulated and the average number of contour crossings per mile was determined (Table VII). Tangency contacts which were not true crossing were counted as one crossing each.
3. Then, the grid was laid over on northeast-southwest orientation covering substantially the same area (Figure 9b). Contour crossings were again counted and the average crossing per mile was determined.
4. The general or overall average contour crossings per mile was calculated. The product of the contour crossing per mile and the contour interval (40 feet) divided by the constant 3361 is equivalent to average slope, Sm, of the land in the cell.

Thus;

$$Sm = \frac{I \times N}{5280 \times 0.6366} \times 100$$

$$= \frac{I \times N}{3361} \times 100$$

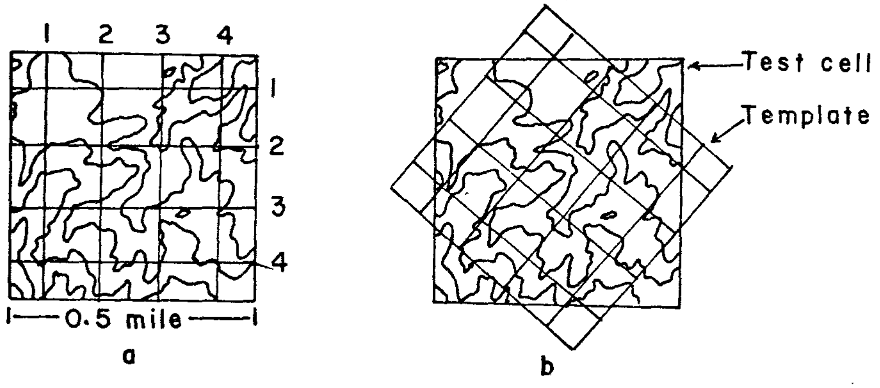


FIG. 9. DIAGRAMS SHOWING THE USE OF TEMPLATE IN DETERMINING AVERAGE SLOPE IN THE TEST CELL. (a) N-S ORIENTATION AND (b) NE-SW ORIENTATION. TOTAL LENGTH OF LINE IS 2 MILES.

TABLE VII. DATA OBTAINED FROM ANALYSIS OF CELLS IN FIG. 9 FOR AVERAGE SLOPE

	Contour Crossing			
Line	N-S	E-W	NE-SW	NW-SE
1	4	6	3	5
2	6	10	6	6
3	8	7	6	6
4	8	9	3	9
Total crossings for 2-mile line	26	32	18	25
Average crossing per mile	13	16	9	13

where;

Sm = average slope in percent

I = contour interval, 40 feet

N = general average contour crossing per mile

5280 = feet per mile

0.6366 = value derived by Wentworth (1930)

The general average crossings per mile or N in Wentworth's equation was 12.75. Substituting 12.75 to N and solving for Sm gave 15.3% as average slope.

The average slope of the land sloping at certain direction may also be calculated by using the average contour crossing obtained in that particular direction. For instance, the average slope of the land sloping on north-south direction would be 15.6 percent since the average contour crossing mile on a north-south direction is 13 (Table VII).

Slope Length, SL. The average length of slope of the land was estimated using both aerial photographs and topographic maps. The stereoscopic image afforded by aerial photographs made the drawing of the slope line accurate. However, because of image distortion and relief displacement, the line was transferred and measured on topographic maps. Average slope length was determined based on at least ten observations depending on the complexity and direction of slope.

Slope length represents the length of land surface from the point of change of slope (Knickpoint), that is, the length measured through its line of uniform slope. In Figure 10, for example, line AB has

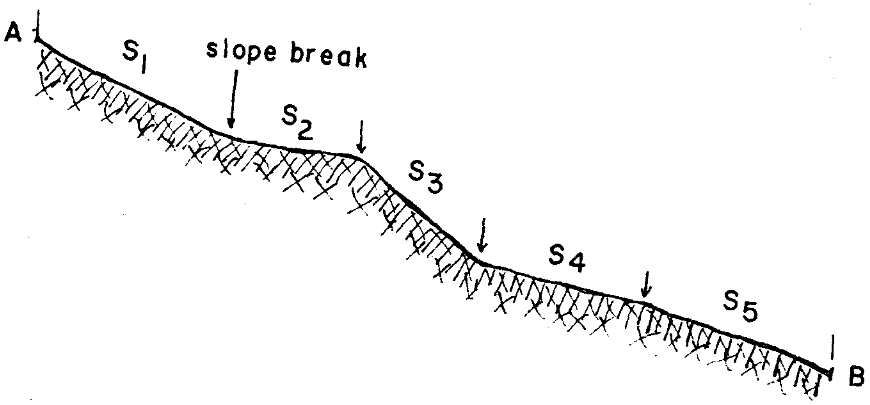


FIG. 10. DIAGRAM SHOWING SECTIONS OF GROUND SURFACES DIVIDED INTO SEGMENTS OF UNIFORM SLOPE. THE AVERAGE SLOPE LENGTH IS EQUIVALENT TO: $SL = \frac{S_1+S_2+S_3+S_4+S_5}{5}$.

five segments, each represents a slope length. The average slope length of the whole section AB will then be equivalent to the sum of the length of the five segments divided by five. The use of aerial photographs facilitate the division of a section into segments of uniform slope. It would be very difficult to accomplish such sectioning on topographic map because of relatively wide contour intervals and the absence of stereoscopic image.

Slope Length Curvature, Slc. Slope length curvature refers to the curvature of slope line measured along the slope length direction. Slope length curvature in the test cell was estimated on topographic map as the ratio between two elevation differences. In Figure 11 slope length curvature is the ratio of the elevation difference between A and C to elevation difference between A and B. Or, if the slope gradient above and below A are known, the slope length curvature is equivalent to the ratio of slope gradient above A to slope gradient below A.

Values of slope length curvature greater than unit indicate concave slope and less than unity indicate convex slope. Slope length curvature was measured on sections of ground surfaces where the slope length was determined.

Slope Width Curvature, Swc. Slope width curvature is the angular measure of the nearest inflection of the contour, the measurement being made on the upslope side. The slope width curvature of the contour angle YXZ in Figure 11, for example, can be determined by locating two points, Y and Z on topographic map on either side of the site X and at the same level but at about 500 feet ground distance. Bearings to Y and Z from X establish the angle subtended at X which represent the slope width curvature. Angles greater than 180 degrees indicate slope width concavity and if the angle is less 180 degrees, a convexity. The average slope width curvature was based on ten observations.

Land Texture Ratio, TL. Land texture ratio was proposed by Smith (1958) as the number of crenulations on the contour line having the maximum number of such crenulations within a given drainage basin divided by the perimeter of the drainage basin. Each sharp outward bend in the contour is considered to represent a stream channel and therefore reflects the actual spacing of the drainage lines even though they are not shown on the map as individual streams.

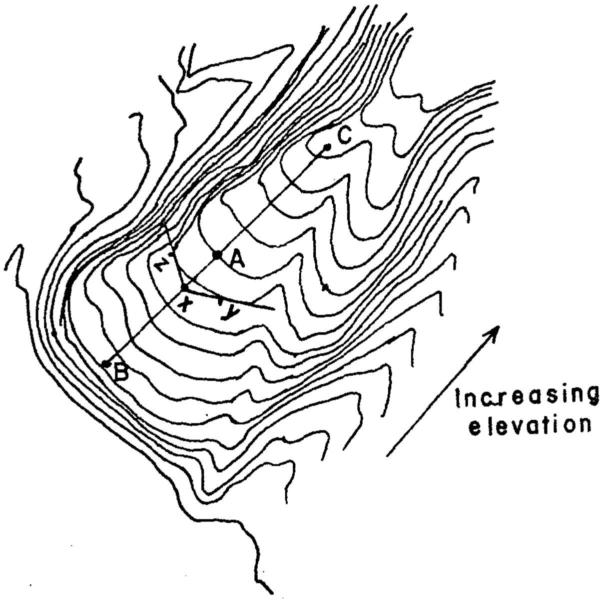


FIG. 11. SLOPE LENGTH AND SLOPE WIDTH CURVATURES ESTIMATION ON TOPOGRAPHIC MAP. SLOPE LENGTH CURVATURE IS EQUIVALENT TO THE ELEVATION DIFFERENCE BETWEEN A AND C DIVIDED BY THE ELEVATION DIFFERENCE BETWEEN A AND B. SLOPE WIDTH CURVATURE IS BEARINGS TO Y AND Z FROM X.

Land texture ratio can be expressed by the equation TL=N/P, where TL represent the land texture ratio in miles^{-1}, N is the number of crenulations on the selected contour, and P is the length of the perimeter of the drainage basin given in miles.

Selection of contour with the greatest number of crenulations is the major problem in using the Smith's method of calculating land texture ratio particularly in highly dissected region. Consequently, a modified method which involved the use of aerial photographs was used in determining land texture ratio in the test cells.

The procedures followed in this study were as follows:

1. Each cell drawn on aerial photographs was examined with a pocket stereoscope. Streams, gullies, rivulets and all natural flow channels in the cell were marked with a red grease pencil.
2. A grid that was prepared for average slope determination was used. The grid was laid over the cell on north-south orientation (Figure 12). All streams or crenulation crossing the line were counted, tabulated and the average number of stream crossings per mile was determined (Table VIII). In a similar manner, tangency contacts were counted as one crossing each.
3. The grid was then laid over on northeast-southwest orientations (Figure 12b). Again, stream crossings were counted and the average stream crossings were determined.
4. The general average stream crossings per mile was calculated, and land texture ratio was calculated as TL=N/P, where N is the average number of stream crossings per mile, and P is the perimeter of cell which is equal to 2 miles.

Using equation TL=N/P where N is the average stream crossings per mile and P is the perimeter of test cell which is 2 miles, the land texture ratio of the cell presented in Figure 12 will be equivalent to 6.5 miles^{-1}.

Drainage Density, Dd. Drainage density within a test cell is defined by the following equation:

$$Dd = \frac{L}{A}$$

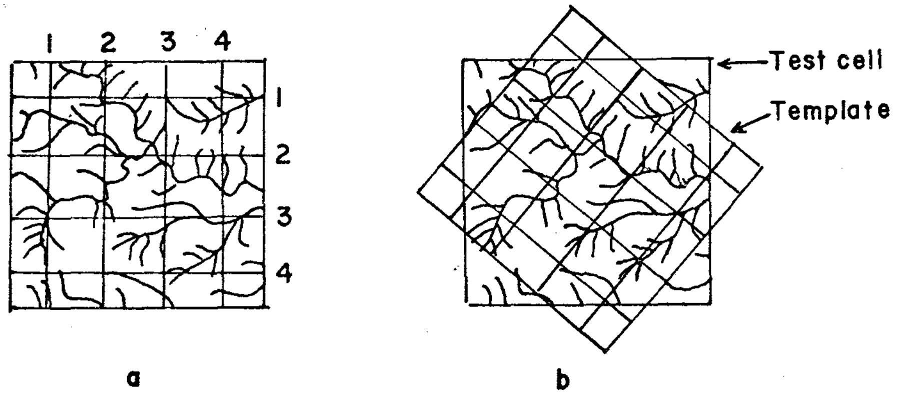


FIG. 12. DIAGRAMS SHOWING THE USE OF TEMPLATE IN DETERMINING LAND TEXTURE RATIO IN THE TEST CELL. (a) ON N-S ORIENTATION AND (b) ON NE-SW ORIENTATION. TOTAL LENGTH OF LINE IS 2 MILES.

TABLE VIII. DATA OBTAINED FROM ANALYSIS OF CELL IN FIG. 12 FOR LAND TEXTURE RATIO

	Stream Crossings			
Line	N-S	E-W	NE-SW	NW-SE
1	6	6	3	3
2	7	8	6	6
3	7	5	5	6
4	8	3	6	3
Total crossings for 2 miles	28	22	20	18
Average/mile	14	11	10	9
General average stream crossings per mile = 11				

where Dd is drainage density in miles per square miles, L is the total length of stream or flow channels in miles in the test cell and A is the area of the cell which is equivalent to 0.25 square miles.

The first step was to draw all the flow channels within the cell by stereoscopic examination of aerial photographs. The delineations were then transferred on to a topographic map where the total length was measured by means of the scale on the map.

Ruggedness Number, Rn. Melton (1957) claimed ruggedness number to be a dimensionless number which can be used for geometric similarity comparisons of terrain. He calculated ruggedness number of an area by obtaining the product of drainage density and local relief both expressed in the same unit. Ruggedness number of a test cells was estimated according to Melton's definition.

Mean Gully Depth, Gd. Mean gully depth as used in this paper refers to the average depth of valleys and gulches including gullies with no less than 20 feet depth. It was calculated on the topographic maps using the Pike (1961) method but was modified by also using the aerial photographs. Pike's method was adapted from Wentworth's (1930) equation for estimating average slope of an area.

The equation used for estimating mean fully depth in the test cell was:

$$Gd = \frac{I \times N}{Sc}$$

where Gd is the mean gully depth in feet, I is the contour interval which is 40 feet, N is the average contour crossing per mile and Se is the slope direction change per mile. The I and N used in this equation are the same I and N used in estimating average slope of the land in the test cell (Table VII). Therefore, Sc is the only value in the equation that needs to be determined.

Pike (1961) calculated the number of slope direction change on a topographic map. The method was time consuming and involved considerable training in map reading. In this study the number of slope direction change per mile in the test cell was determined on aerial photographs. The three-dimensional image afforded by a stereopair of aerial photographs made the calculation of slope direction change fast and accurate.

Application of Data Processing and Statistical Analysis

Undoubtedly, statistical analysis is the only rational method of analyzing the data obtained by the quantitative measurements of terrain factors and this approach has been used by every investigator since 1947 without exception (for example, Strahler, 1956; Salisbury and Valle, 1963; Schumm, 1956).

Most of the statistical analysis of terrain data collected in this study were performed on the IBM/360 computer at the University of Hawaii Statistical and Computing Center.

All the data were placed on cards using the IBM 29 Key Punch Machine and the Biomedical Computer Programs adapted for the IBM/360 computer were utilized.

Statistical Summary.

A statistical summary was obtained for each of the eight great soil groups on Oahu and six soil associations on Kauai. The summary included the mean of each of the terrain factors obtained from each of the soil areas studied, standard errors, standard deviation, coefficient of variation, variance and sum of squares.

Analysis of Variance. The first step in the statistical analysis of the terrain factors was the analysis of variance to determine the "F" values so that judgements could be made as to whether or not there were any significant difference in the mean values of terrain factors of the various great soil groups on Oahu and soil associations on Kauai. Details of the testing procedures are readily available in textbooks of statistics.

Analysis of variance was done separately for each of the ten terrain factors studied based on the hypothesis that $\bar{x}_1 = \bar{x}_2 \ldots\ldots \bar{x}_n$, where n = 8 great soil groups on Oahu; 6 soil associations on Kauai. The sources of variation and the degrees of freedom involved are shown on Table IX.

Multiple Range Test. When the analysis of variance revealed significant differences among $\bar{x}_1$, $\bar{x}_2$, $\bar{x}_3 \ldots\ldots \bar{x}_n$, the Duncan Multiple Range test was used to determine which of the means differed significantly from each other (Duncan, 1955). The test includes an analysis of variance table, a ranking of cell means, and listing of all homogeneous subsets for each set of range cards. The results of the multiple range test gave information as to which terrain factor or factors could be used to separate any two of the great soil groups or soil associations.

TABLE IX. ANALYSIS OF VARIANCE MODEL USED IN THE INVESTIGATION OF THE TERRAIN FACTORS

Source	Degrees of Freedom
a. Oahu	
Great soil groups	7
Errors	145
Total	152
b. Kauai	
Soil associations	5
Errors	163
Total	168

Correlation Coefficient. This analysis was performed to demonstrate the existence (or lack of existence) of a relationship between two terrain factors. It was not the purpose of this paper to define the function relating the two attributes but merely to establish the existence of correlation beyond the possibility of a pure change relationship. The results of this analysis included sums, mean of each of terrain factors, cross product deviations, standard deviation, variance, covariance matrix and correlation matrix.

Discriminant Analysis for Two Groups. This test directs the computation of a set of linear functions for the purpose of classifying an individual into one of the two groups. Discriminant analysis of two great soil groups on Oahu using four terrain factors was performed. The two great soil groups were Tropohumult (Order Ultisol) and Gibbsihumox (Order Oxisol). The four terrain factors included in the analysis were average elevation, average slope, slope length and drainage density.

The purpose of this analysis was to determine whether or not the cells established in the two great soil groups actually belonged to those populations defined on the basis of the four terrain factors. There were 44 cells in the Tropohumult area and 24 cells in the Gibbsihumox area. If the 44 cells measured in the Tropohumult soil area really belonged to this population, then all these cells can be discriminated from the 24 cells established in the Gibbsihumox area and be classified within the Tropohumult.

The dimensional plane that effectively separates the two clusters of cells is the discriminant function based on the equation:

$$Z = b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4$$

where Z = discriminant function

b = discriminant function coefficients of the terrain factors, b_1 for average elevation b_2 for average slope, b_3 for slope length and b_4 for drainage density.

x = values of terrain factor measured in the cell, x_1 for average elevation, x_2 for average slope, x_3 for slope length and x_4 for drainage density.

To test the validity of this equation, ten cells were drawn from other Gibbsihumox areas and ten cells from Tropohumult area and the same four terrain factors were measured from each cell. Values were substituted in Equation (1) using the same discriminant function coefficient, b_1 for Ea, b_2 for Sm, b_3 for SL and b_4 for Dd. Cells were classified into one of the two great groups based on their Z values.

Discriminant Analysis for Three Groups. This analysis performed multiple discriminant analysis for the purpose of classifying individuals into group of more than two populations. The complexity of discriminant analysis increased when more than two populations were involved and the details of the methods were not included in this study. Kendall (1961) developed the theory and discussed the equation in detail. Discriminant analysis of three great soil groups belonging to one soil Order was performed using the four terrain factors: Local relief (RL), Average slope (Sm), Slope length (SL) and Drainage density (Dd). These great soil groups were Haplustox, Eutrorthox and Gibbsihumox, all Oxisols.

Stepwise Discriminant Analysis. This analysis performed multiple discriminant analysis in a stepwise manner. At each step one variable (a terrain factor) was entered into a set of discriminating variables. A variable was deleted if the F-value was too low. This program analysis determined which of the four terrain factors, Ea, Sm, SL and Dd, was the most efficient in separating the three great soil groups--Haplustox, Eutrorthox and Gibbsihumox. The analysis also classified the cells into three great soil groups and showed which cell or cells were not in agreement.

Numerical Classification or Cluster Analysis. The numerical classification is a procedure which involved computing a statistical coefficient and estimating the similarity of each test cell to every other cell in the study. The calculation of the coefficient for all possible comparison of the cells yielded a matrix table of similarity coefficient among cells which indicated the quantitative similarity of each cell to every other cells.

Cipra, et al. (1970) applied a multivariate statistical procedure of numerical classification to 59 soils using 21 morphological and laboratory characteristics of model soil profiles from 9 Soil Orders. He found that the techniques revealed numerous logical similar relationship among the soils which generally agreed with present classification except for the Ultisols, Vertisols, Aridisols and the single Oxisol. The results indicated that the Orders Mollisols, Alfisols, Entisols and Inceptisols may be at least partially defined in many of the 21 characteristics which were used.

Numerical classification of cell data was employed in this study on the assumption that (a) no information about the soil was available for the area and (b) if these terrain factors were related to soil, then the map compiled on the basis of cell grouping through computer programming will be closely related to the map produced by SCS.

Numerical classification was performed on the following sets of terrain data measured on Kauai:

1. Original 169 test cells measured on 6 soil associations using the 10 terrain factors.
2. On 108 test cells (0.5 mile square) in grids of uniform sampling established on 27-square mile area in eastern Kauai (Figure 14). Five terrain factors were used. These includes average elevation (Ea), local relief (RL), average slope (Sm), slope length (SL) and land texture ratio (TL).

The decision to use these 5 terrain factors was based on two important considerations (a) high efficiency in differentiating between the two soil association areas and (b) the ability to measure all the factors on the topographic maps.

Data Standardization. Because of the different units of measurement in the terrain data, it became necessary to standardize the data before numerical grouping of test cell terrain data were performed. This was done through computer programming of the equation:

$$X_{ij} = \frac{x_{ij} - x_j}{S_j} + 5$$

where X_{ij} = standardized value of terrain factor, j for cell, i.

x_{ij} = actual value of terrain factor, j for cell, i.

x_j = mean based on actual data of terrain factor, j.

S_j = standard deviation of terrain factor, j.

RESULTS AND DISCUSSION

General

The principal objective of this study was to determine whether or not different soil areas (great soil groups on Oahu and soil associations on Kauai) can be separated by means of quantitative terrain factors. Consequently, statistical analysis of terrain data measured on different soil areas were performed. The summary of statistical data for each of the ten terrain factors measured on different soil areas on Oahu and Kauai are presented in Appendix A and Appendix B.

The results of the statistical analysis indicated that there were some significant relationship between the quantitative terrain factors and the various soil areas studied on the two islands. Within the study areas, more than 70 percent of the various great soil group combinations have one or more terrain factors which were significantly different.

Results Obtained on Oahu

Efficiency of Various Terrain Factors

The terrain factors selected for the investigation were tested by analysis of variance to determine whether or not the mean values of the various great soil groups were significantly different. Results of analysis of variance are shown in Appendix C.

Table X shows the mean values of ten terrain factors obtained from eight great soil groups on Oahu. The F-values indicate that the means were significantly different at the 99 percent significance level. The Duncan Multiple Range test (Duncan, 1955) was used to determine which comparisons were significant and to determine which terrain factor or factors can be used to distinguish between two great soil

TABLE X. MEAN VALUES OF TERRAIN DATA OBTAINED FROM EIGHT GREAT SOIL GROUPS ON OAHU

Great Soil Group[b]	Terrain Factor[a]									
	Ea	RL	Sm	SL	Slc	Swc	TL	Dd	Rn	Gd
TH	640.09	378.70	30.70	1086.80	0.83	40.71	4.02	13.60	5643.09	174.04
HU	575.38	407.85	33.22	964.84	0.99	44.70	3.58	12.87	6051.61	246.40
GH	1313.00	582.91	58.15	451.48	1.13	30.08	4.98	16.65	13234.04	444.74
EO	551.50	239.00	14.31	1446.59	0.89	48.06	1.80	5.74	1533.60	93.87
RU	683.50	553.16	36.97	663.10	0.61	39.78	3.54	12.15	7383.33	289.47
DA	1082.15	526.61	33.92	785.42	1.10	41.50	2.98	9.72	5177.30	201.44
HT	965.71	202.85	13.62	1269.04	1.64	43.78	2.78	9.25	1818.28	84.51
UT	696.66	153.33	10.35	1542.21	1.03	58.50	2.33	8.00	1325.33	66.91
F-value[c]	10.25	10.57	25.20	14.03	6.44	4.85	13.50	15.86	21.38	20.59

[a] Ea=Average elevation, RL=Local relief, Sm=Average slope, SL=slope length, Slc=slope length curvature, Swc=slope width curvature, TL=land texture ratio, Dd=drainage density, Rn=Ruggedness number and Gd=gully depth.

[b] TH=Tropohumult, HU=Haplustox, GH=Gibbsihumox, EO=Eutrorthox, RU=Rhodustalf, DA=Dystrandept, HT=Humitropept, UT=Ustropept.

[c] All F-values significant at 99 percent level of significance.

group areas.

Tables XI and XII show the efficiency of the various terrain factors at the 95 and 99 percent significance levels, respectively. If there were any significant difference in the mean value, the particular terrain factor was considered to be efficient in distinguishing the two great soil groups; for example, if the mean values of the average slope (Ea) of the Tropohumult (TH) and Eutrorthox (EO) were significantly different, then this terrain factor was considered to be efficient in that comparison. The efficiency of a terrain factor is then the proportion of the possible combinations of great soil groups in which the difference between values of that terrain factor is significant; for example, in Table XI the average slope (Sm) was significantly different in 19 of the 28 possible comparisons of the eight great soil groups on Oahu. The efficiency of the average slope in differentiating between the great soil group areas was, therefore, 68 percent. Table XII shows that the efficiency of the average slope at 99 percent level of significant was also 68 percent.

Table XI shows that local relief (RL) and slope length (SL) were the highest ranked significant factors in distinguishing two great soil group areas. Average slope (Sm), drainage density (Dd) and ruggedness number (Rn) followed closely in effectiveness rating. Mean gully depth (Gd), although not extremely effective, was necessary to differentiate some great soil group areas. It would undoubtedly be more effective in areas where more mature drainage systems have developed under the influence of the physical characteristics of the terrain.

TABLE XI. SIGNIFICANT TERRAIN FACTORS WHEN COMPARING GREAT SOIL GROUPS ON OAHU (95 PERCENT LEVEL OF SIGNIFICANCE)

Great Soil Group	Ea	RL	Sm	SL	Slc	Swc	TL	Dd	Rn	Gd
TH-HU										x
TH-GH	x	x	x	x	x	x	x	x	x	x
TH-EO		x	x	x			x	x	x	x
TH-RU		x		x						x
TH-DA	x	x		x			x	x		
TH-HT	x	x	x		x		x	x	x	
TH-UT		x	x	x		x	x	x	x	
HU-GH	x	x	x	x		x	x	x	x	x
HU-EO		x	x	x			x	x	x	x
HU-RU		x		x	x					
HU-DA	x							x		
HU-HT	x	x	x		x			x	x	x
HU-UT		x	x	x		x	x	x	x	x
GH-EO	x	x	x	x		x	x	x	x	x
GH-RU	x		x	x	x	x	x	x	x	x
GH-DA	x		x	x		x	x	x	x	x
GH-HT	x	x	x	x	x	x	x	x	x	x
GH-UT	x	x	x	x		x	x	x	x	x
EO-RU		x	x	x	x		x	x	x	x
EO-DA	x	x	x	x			x	x	x	x
EO-HT	x				x			x		

TABLE XI. (CONTINUED) SIGNIFICANT TERRAIN FACTORS WHEN COMPARING GREAT SOIL GROUPS ON OAHU (95 PERCENT LEVEL OF SIGNIFICANCE)

Great Soil Group	Ea	RL	Sm	SL	Slc	Swc	TL	Dd	Rn	Gd
EO-UT										
RU-DA	x				x					
RU-HT		x	x	x	x				x	x
RU-UT		x	x	x	x	x		x	x	x
DA-HT		x	x	x	x				x	
DA-UT	x	x	x	x		x			x	x
HT-UT					x					
Total	15	20	19	20	13	11	15	19	19	18
Percent	53	71	68	71	46	39	53	68	68	64

TABLE XII. SIGNIFICANT TERRAIN FACTORS WHEN COMPARING GREAT SOIL GROUPS ON OAHU (99 PERCENT LEVEL OF SIGNIFICANCE)

Great Soil Group	Ea	RL	Sm	SL	Slc	Swc	TL	Dd	Rn	Gd
TH-HU										
TH-GH	x	x	x	x	x	x	x	x	x	x
TH-EO		x	x	x			x	x	x	
TH-RU		x		x						x
TH-DA	x							x		
TH-HT			x		x					
TH-UT		x	x			x	x	x		
HU-GH	x	x	x	x		x	x	x	x	x
HU-EO		x	x	x			x	x	x	x
HU-RU					x					
HU-DA	x									
HU-HT			x		x					x
HU-UT		x	x	x						x
GH-EO	x	x	x	x		x	x	x	x	x
GH-RU	x		x		x		x	x	x	x
GH-DA			x				x	x	x	x
GH-HT		x	x	x	x		x	x	x	x
GH-UT	x	x	x	x		x	x	x	x	x
EO-RU		x	x	x			x	x	x	x
EO-DA	x	x	x	x				x	x	
EO-HT					x					

TABLE XII. (CONTINUED) SIGNIFICANT TERRAIN FACTORS WHEN COMPARING GREAT SOIL GROUPS ON OAHU (99 PERCENT LEVEL OF SIGNIFICANCE)

Great Soil Group	Ea	RL	Sm	SL	Slc	Swc	TL	Dd	Rn	Gd
EO-UT										
RU-DA	x				x					
RU-HT		x	x	x	x				x	x
RU-UT		x	x	x		x			x	x
DA-HT		x	x		x					
DA-UT		x	x	x						
HT-UT										
Total	9	16	19	14	10	6	11	13	13	14
Percent	32	57	68	50	35	21	39	46	46	50

Average elevation (Ea) and land texture ratio (TL) were equally effective but not as effective as average slope and drainage density. Slope length curvature (Slc) and slope width curvature(Swc) proved to be least effective although they were useful in several great soil group comparisons where there were only a few other significant factors.

Based on Table XI and XII, five terrain factors appeared effective in separating various combinations of eight great soil group areas on Oahu. These factors were as follows:

1. Local relief (RL)
2. Slope length (SL)
3. Average slope (Sm)
4. Drainage density (Dd)
5. Ruggedness number (Rn)

Distribution of Great Soil Group Areas by Terrain Factors

This study included eight great soil group areas which could be arranged into 28 different combinations and which could be tested one against another. If the mean value for a given terrain factor of a given great group area were significantly different from the mean value of another area, these two great soil group areas were considered to be distinguishable one from the other by that terrain factor. Table XIII is a graphical representation summarizing the information presented in Table XI and conveniently showing which of the terrain factor or factors could be used to distinguish one great soil group area from another.

Comparison of the various great soil group areas showed that all but one of the 28 combinations could be differentiated by one or more

TABLE XIII. SUMMARY OF SIGNIFICANT DIFFERENCES BETWEEN OAHU GREAT SOIL GROUP AREAS. DATA ARE BASED ON DUNCAN MULTIPLE RANGE TEST, 95 PERCENT SIGNIFICANCE. TH=TROPOHUMULT, HU=HAPLUSTOX, GH=GIBBSIHUMOX, EO=EUTRORTHOX, RU=RHODUSTALF, DA=DYSTRANDEPT, HT=HUMITROPEPT AND UT=USTROPEPT.

E_a- Average elevation
R_L- Local relief
Sm- Average slope
S_L - Slope length
S_{Lc}- Slope length curvature
Swc- Slope width curvature
T_L - Land texture ratio
Dd- Drainage density
Rn- Ruggedness number
Gd- Gully depth

Terrain factors which can be used to distinguish between two great soil groups are listed in the intersecting square.

GREAT SOIL GROUP	TH	HU	GH	EO	RU	DA	HT	UT
TH								
HU	G_d							
GH	E_a T_L R_L S_{Lc} D_d Sm Swc Rn S_L Gd	E_a T_L R_L D_d Sm Rn S_L Swc						
EO	R_L T_L Sm Dd S_L Rn G_d	R_L T_L Sm Dd S_L Rn Gd	E_a T_L R_L Sm Dd S_L Rn Swc G_d					
RU	R_L S_L Gd	R_L S_L S_{Lc}	E_a T_L Sm Dd S_L Rn S_{Lc} Gd Swc	R_L T_L Sm Dd S_L Rn Swc Gd				
DA	E_a T_L R_L S_L Dd	E_a D_d	E_a T_L Sm Dd S_L Rn Swc Gd	E_a T_L R_L Dd Sm Rn S_L Gd	E_a S_{Lc}			
HT	E_a S_{Lc} R_L T_L Sm Dd Rn	E_a Dd R_L Rn Sm Gd S_{Lc}	E_a T_L R_L Dd Sm Rn S_L Gd S_{Lc} Swc	E_a S_{Lc} Dd	R_L S_{Lc} Sm Rn S_L Gd	R_L S_{Lc} Sm Rn S_L		
UT	R_L Swc Sm T_L S_L D_d Rn	R_L T_L Sm Dd S_L Rn Swc Gd	E_a T_L R_L Dd Sm Rn S_L Swc Gd	NONE	R_L Swc Sm Dd S_L Rn S_{Lc} Gd	E_a Swc R_L Rn Sm Gd S_L	S_{Lc}	

of their quantitative terrain factors. Table XIII indicates that Ustropept (UT) and Eutrorthox (EO) areas could not be separated by any of the terrain factors. The external features of these two great soil group areas can be compared by examining the aerial photo stereogram in Plate 1 and 3 (Appendix E). Stereoscopic examinations of the photographs of these two great soil group areas indicated that the terrain features do not differ very much to be able to separate them visually. Duncan Multiple Range test showed that the mean values of these two areas for any of the terrain factors did not differ significantly.

In the case of Tropohumult (TH) and Haplustox HU), only mean gully depth could be used to distinguish between these two groups (Plates 1 and 4, Appendix E). Table X indicates that the difference in the terrain data of these two great soil group areas, except for gully depth, was not sufficiently large to be significant. Similarly, only one terrain factor, slope length curvature, was significant when comparing the Humitropept and Ustropept areas. The landscape features of these two areas may be examined in the aerial photograph stereogram (Plate 3, Appendix E).

Each of the remaining great soil group combinations had at least two distinguishing terrain factors. Such results indicate that differences in several aspects of topography of the great soil groups on Oahu are of sufficient magnitude to be characterized by a number of quantitative terrain factors. Tables XI, XII and XIII shows the terrain factors which were significantly different and Table X shows the mean values for each great soil groups. Aerial photograph stereograms in Appendix E illustrate the physiographic characteristics of the eight great soil group areas.

Discriminant Function Analysis to Distinguish the Tropohumult and Gibbsihumox Areas

Discriminant function analysis is one of the powerful tools of numerical classification which can be used to assign samples to populations previously defined on the basis of several variables considered simultaneously (Harbaugh and Merriam, 1968).

A set of n_1 samples from population 1 and a set of n_2 samples from population 2 can be described by the variables as:

$$A_1,\ B_1,\ C_1 \ldots\ldots K_1$$

$$A_2,\ B_2,\ C_2 \ldots\ldots K_2$$

The sum of variables, sum of squares of variables and sum of cross products for each population are accumulated and used in the series of equations to produce the linear discriminant function and related terms. Krumbein and Graybill (1965) and Davis and Sampton (1966) discussed in detailed the series of equations used to develop a linear discriminant function:

$$Z = b_1A + b_2B + b_3C + \ldots\ldots\ldots + b_kK \qquad (3)$$

where Z is the discriminant function, b the discriminant coefficient of the variable A, B, C,....K.

There were two reasons for performing the discriminant analysis--first was to develop the equation which may separate two great soil group areas based on selected terrain factors and second to determine whether or not the cells studied in the two great soil group areas actually belong to those populations defined on the basis of some terrain factors. There were 44 cells studied in the Tropohumult area and 24 cells in the Gibbsihumox area. If the 44 cells measured in the Tropohumult soil truly belonged to the population, then the majority, if not all, of these cells should be discriminated from the 24 cells in the Gibbsihumox area.

In this analysis only 4 terrain factors were utilized in the development of discriminant function for Tropohumult and Gibbsihumox areas. These factors include average elevation (Ea), average slope (Sm), slope length (SL) and drainage density (Dd). The reason for selecting these terrain factors is that these factors can be quantified with the use of topographic map with reasonable degree of accuracy without much difficulty in measurements.

The detailed steps of computation are not given although their sequence is described briefly as follows:

The first step was to determine the mean values of the variables (terrain factors) obtained for the two great soil group area and to determine the difference between the means. The mean values of terrain factors for the two groups are presented in Table XIV.

TABLE XIV. MEAN VALUES OF FOUR TERRAIN FACTORS OBTAINED FOR THE TROPOHUMULT AND GIBBSIHUMOX AREAS

	Mean Value		
Terrain Factor	Tropohumult	Gibbsihumox	Difference
Average elevation	640.09	1313.00	-672.90
Average slope	30.25	58.15	-27.89
Slope length	1086.80	415.48	635.35
Drainage density	13.60	16.64	-3.04

The next step was to determine the sum of square S_A, S_B, S_C and S_D (Equation 4) and the cross products with the combinations of terrain factors represented by S_{AB}, S_{AB},......S_{CD} (Equation 5). Since there were four terrain factors, there were six cross products.

$$S_A = (\Sigma A_1^2 + \Sigma A_2^2) - \frac{(\Sigma A_1)^2}{n_1} - \frac{(\Sigma A_2)^2}{n_2} \qquad (4)$$

$$S_{AB} = (\Sigma A_1 B_1 + \Sigma A_2 B_2) - \frac{\Sigma A_1 \Sigma B_1}{n_1} - \frac{\Sigma A_2 \Sigma B_2}{n_2} \qquad (5)$$

The sum of squares, S_B, S_C, and S_D were computed using the corresponding terrain data. The notation A refers to average elevation, B to average slope, C to slope length and D to drainage density. The numbers 1 and 2 refer to Tropohumult and Gibbsihumox areas, respectively.

The other cross products, S_{AC}, S_{AD}, S_{BC}, S_{BD}, and S_{CD} were determined using the corresponding terrain data. The following shows the matrix format for the sum of squares and cross product.

$$\begin{array}{ccccc}
 & A & B & C & D \\
A & S_A & S_{AB} & S_{AC} & S_{AD} \\
B & S_{AB} & S_B & S_{BC} & S_{BD} \\
C & S_{AC} & S_{BC} & S_C & S_D \\
D & S_{AD} & S_{BD} & S_{CD} & S_D
\end{array}$$

A series of linear equations were formed based on the matrix format and the unknown coefficients b_1, b_2, b_3, and b_4.

$$\begin{aligned} S_A b_1 + S_{AB} b_2 + S_{AC} b_3 + S_{AD} b_4 &= \bar{A}_1 - \bar{A}_2 \\ S_{AB} b_1 + S_B b_2 + S_{BC} b_3 + S_{BD} b_4 &= \bar{B}_1 - \bar{B}_2 \\ S_{AC} b_1 + S_{BC} b_2 + S_C b_3 + S_{CD} b_4 &= \bar{C}_1 - \bar{C}_2 \\ S_{AD} b_1 + S_{BD} b_2 + S_{CD} b_3 + S_D b_4 &= \bar{D}_1 - \bar{D}_2 \end{aligned} \qquad (6)$$

Equation 6 is a system of four equations and four unknowns. The right hand side of the equation represents the difference in the mean values between the two great soil groups (Table XIV). The four unknowns are the discriminant function coefficients b_1, b_2, b_3 and b_4 for average elevation, average slope, slope length and drainage density, respectively. The simultaneous equations (6) are solved to obtain the values for b_1, b_2, b_3 and b_4 which can be substituted in Equation 3. The unknown coefficients are solved by means of matrix inversion which is one of the difficult problems in discriminant function analysis.

Matrix inversion is laborious and for large matrix (4 x 4) the use of high-speed digital computer is necessary. In this particular case, the matrix format was inverted by using an inversion routine program prepared by Rocketdyne, a division of North American Aviation. For small symmetrical matrix, and if a computer is not available, the Abbreviated Doolittle Procedure of matrix inversion may be used (Krumbein and Graybill, 1965).

The solution of Equation 6 yields the coefficient vector:

$$b = \begin{array}{cc} b_1 & -0.00008 \\ b_2 & -0.00179 \\ b_3 & 0.00011 \\ b_4 & 0.00196 \end{array} \qquad (7)$$

Thus, the corresponding discriminant function of Equation 3 becomes:

$$Z = -0.00008A + -0.00179B + 0.00011C + 0.00196D \qquad (8)$$

The discriminant function, Z was computed for Tropohumult and Gibbsihumox by using Equation 8. Table XV shows the results of the final computation.

TABLE XV. DISCRIMINANT FUNCTION, Z, FOR TWO GREAT SOIL GROUP AREAS ON OAHU BASED ON FOUR TERRAIN FACTORS

Great Soil Group	Sample Size	Mean Z
Tropohumult	44	0.04417
Gibbsihumox	24	-0.12861
Discriminant Index, Z_0, 1/2[0.04417 + (-0.12861)] = -0.04222		

A set of terrain data may be substituted into Equation 8 to determine the values for Z. Based on the distribution on the (K-1)-dimensional plane, $Z = Z_0$, the values are assigned to one or the other of the two populations.

The Z value of each cell measured for the four terrain data in the Tropohumult and Gibbsihumox areas was determined and classified according to the calculated discriminant index, Z_0. Cells with Z greater than -0.04222 were classified in the Tropohumult area and cells with Z less than -0.04222 were assigned to Gibbsihumox. The result of this classification are presented in Table XVI.

TABLE XVI. SUMMARY OF THE RESULT OF CLASSIFICATION OF CELLS ON THE BASIS OF DISCRIMINANT FUNCTION

	Total Number of Cell	Number of Cells Classified As Tropohumult	Number of Cells Classified As Gibbsihumox
Tropohumult	44	43	1
Gibbsihumox	24	1	23

Table XVI shows that one out of 44 cells in the Tropohumult area was classified as Gibbsihumox and one out of 24 Gibbsihumox cells was classified as Tropohumult. Since only one cell in each of the soil area does not fall within the predicted area it may be concluded that the 44 cells established on Tropohumult area are strongly likely to belong to that population and the 24 cells drawn in Gibbsihumox area likewise belong to Gibbsihumox.

Test of Significance of Multivariate Difference

To test whether or not the two cells measured for various terrain factors were from different populations, a significance test, Mahalanobis' D^2 was used. This is a measure of the distance between the two sample cluster multivariate means. Rao (1952) derived the equation for determining D^2 as:

$$D^2 = b_1 \Delta \bar{A} + b_2 \Delta \bar{B} + b_3 \Delta \bar{C} + b_4 \Delta \bar{D} \qquad (9)$$

where D^2 is the Mahalanobis' Distance, $b_1 \ldots\ldots b_4$ is the discriminant function coefficients (Equation 7) and $\Delta \bar{A}$, $\Delta \bar{B}$, $\Delta \bar{C}$ and $\Delta \bar{D}$ as the mean difference between the two population, (Table XIV).

Based on Equation 9, the D^2 obtained for the Tropohumult and Gibbsihumox cells was 11.40.

The significance of the multivariate difference was tested by the equation:

$$F_{(K,\ n_1 + n_2 - K-1)df} = \frac{n_1 n_2}{(n_1 + n_2)\ (n_1 + n_2 - 2)} \times \frac{n_1 + n_2 - K-1}{K} \qquad (10)$$

where n_1 and n_2 refer to number of cells from Tropohumult and Gibbsihumox areas, respectively, and K refers to number of terrain factors used.

The F value obtained in this particular test was 42.26. The F values required for 5 percent and 1 percent significance levels are 5.70 and 13.69, respectively. These results indicate that the multivariate difference between the two populations was highly significant, rejecting the hypothesis that Population 1 = Population 2.

The discriminant analysis has shown that only one of 44 cells established in the Tropohumult area and one of the 24 cells drawn from Gibbsihumox area may be misclassified. This indicate that the discriminant function analysis, therefore, satisfactorily segregates the two great soil groups. Except in unusual cases, however, this does not mean that every individual cell is uniquely assigned to one population or the other. Obviously, the majority of the cells should be distinguishable if the discriminant is to be useful.

Application of Discriminant Function Analysis to Other Tropohumult and Gibbsihumox Areas on Oahu

In a previous section the discriminant function analysis satisfactorily segregates the 44 Tropohumult cells from 24 Gibbsihumox cells in that particular part of Oahu where the cells were established (Figure 5).

The test was again utilized to confirm the Tropohumult cells and Gibbsihumox cells in other parts of Oahu. Ten cells each of Tropohumult and Gibbsihumox areas were compared using the same four terrain factors which were used previously. The Z value was computed and each of the cells was classified as either Tropohumult or Gibbsihumox based on the discriminant index, $Z_0 = -0.04312$. The discriminant index, Z_0 was determined using Equation 11:

$$Z_0 = \frac{\Sigma Z_1 + \Sigma Z_2}{n_1 + n_2} \tag{11}$$

where Z_0 = discriminant index

Z_1 = total of all TH_2 values

Z_2 = total of all GH_2 values

n_1 = number of TH cells

n_2 = number of GH cells

Again cells with $Z > Z_0$ was assigned to Tropohumult area and cell with $Z < Z_0$ was assigned to Gibbsihumox area. The terrain data obtained from each cell, the Z value and its classification are shown in Table XVII.

Table XVII shows that all cells from the Gibbsihumox areas have Z values indicative of Gibbsihumox. All cells except one from the Tropohumult areas have Z values indicative of this soil group. The one exception (No. 2), although called a Tropohumult, may be a Gibbsihumox, as the analysis suggests, because this particular cell occurs in a transitional soil zone.

TABLE XVII. DATA OF FOUR TERRAIN FACTORS FOR TEN TROPOHUMULT (TH) AND TEN GIBBSIHUMOX (GH) CELLS, THE Z VALUES, AND CLASSIFICATION

Cell	Ea	Sm	SL	Dd	Z Value	class*
TH						
1	620.0	28.5	960.0	8.6	0.0218	TH
2	1827.5	44.1	720.0	10.8	-0.1248	GH
3	490.0	29.2	1460.0	13.9	0.0964	TH
4	260.0	17.7	800.0	12.4	0.0599	TH
5	472.0	35.8	820.0	13.6	0.0151	TH
6	386.5	30.3	600.0	8.4	-0.0027	TH
7	255.5	22.8	1100.0	10.0	0.0794	TH
8	450.0	29.5	840.0	10.7	0.0245	TH
9	226.0	35.4	880.0	9.8	0.0347	TH
10	320.0	37.6	760.0	9.2	0.0087	TH
GH						
1	944.0	39.4	460.0	15.6	-0.0649	GH
2	1000.0	36.1	460.0	14.3	-0.0660	GH
3	1220.0	37.3	520.0	14.8	-0.0781	GH
4	1097.0	42.4	400.0	13.6	-0.0929	GH
5	780.0	37.0	420.0	15.2	-0.0527	GH
6	1054.0	41.7	300.0	13.6	-0.0993	GH
7	763.5	45.9	400.0	13.6	-0.0725	GH
8	1321.0	41.4	360.0	16.6	-0.1076	GH
9	1140.0	50.5	320.0	14.5	-0.1179	GH
10	1060.0	44.5	460.0	14.2	-0.0860	GH

*Class refers to the classification of every cell based on whether or not the Z value is greater than or less than -0.0430. Value greater than -0.0430 was assigned to TH and value less than -0.0430 was placed under GH.

The results indicates, therefore, that the discriminant function analysis can be used satisfactorily to distinguish the Tropohumult and Gibbsihumox areas on Oahu and the discriminant function coefficients obtained for the four terrain factors (Ea, Sm, SL and Dd) can be considered constant.

Further Application of the Discriminant Function Analysis to Tropohumult and Gibbsihumox Areas on Kauai Island

The discriminant function analysis has been used to separate the Tropohumult and Gibbsihumox areas on Oahu. It is the purpose of this section to distinguish the Tropohumult and Gibbsihumox areas on Kauai utilizing the same discriminant function coefficients b_1, b_2, b_3 and b_4 (Equation 7). Tropohumult and Gibbsihumox areas on Kauai were established by classifying the established soil series into great soil group category. Ten cells were selected in each area and the same four terrain factors--average elevation (Ea), average slope (Sm), slope length (SL) and drainage density (Dd) were determined in every cell. The data were substituted into Equation 8 and the Z value of each of the cells were determined. The discriminant index, Z_0 was determined using Equation 11. Table XVIII shows the terrain data and the Z values obtained.

As shown on Table XVIII, seven cells in the Tropohumult area were reclassified as Gibbsihumox. The table indicates that only one cell has Z value that would assign it to Gibbsihumox area. All nine cells have values which would place them in the Tropohumult area.

These results suggest that the discriminant function equation developed for Oahu does not necessarily apply for the analysis of

TABLE XVIII. TERRAIN DATA OBTAINED FROM TEN TROPOHUMULT (TH) AND TEN GIBBSIHUMOX (GH) CELLS ON KAUAI ISLAND

Cell[a]	Ea	Sm	SL	Dd	Z value	Class[b]
TH						
8	460.0	29.9	360.0	5.9	-0.0391	GH
10	290.0	25.3	500.0	5.4	-0.0030	GH
11	503.0	20.4	500.0	5.9	0.0004	GH
29	320.0	27.7	300.0	4.3	-0.0608	GH
60	192.5	22.9	1900.0	7.7	0.3035	TH
61	540.0	35.5	1360.0	10.1	0.0626	TH
62	460.0	42.6	600.0	10.0	-0.0268	GH
65	740.5	40.8	540.0	7.4	-0.0583	GH
80	760.0	46.3	560.0	12.3	-0.0574	GH
83	540.0	25.8	600.0	11.3	-0.0004	GH
GH						
21	390.0	8.5	2000.0	13.4	-0.1497	GH
22	330.0	7.0	1280.0	12.4	0.1269	TH
33	320.0	10.6	1420.0	10.6	0.1323	TH
34	404.0	12.1	1600.0	11.3	0.1439	TH
37	420.0	11.2	1091.0	5.9	0.0779	TH
68	210.0	11.2	1080.0	5.4	0.0925	TH
96	380.0	21.6	1240.0	13.4	0.0936	TH
97	320.0	15.1	1200.0	10.0	0.0989	TH
102	320.0	15.9	1200.0	7.8	0.0934	TH
103	440.0	15.3	1560.0	7.4	0.1235	TH

[a] Refer to Fig.17 for cell location.

[b] Class refers to the classification of every cell based on whether or not the Z value is greater or less than $Z_o = 0.0598$. Value greater than 0.0598 was assigned to TH and value less than 0.0598 was placed under GH.

the Kauai cell areas. A separate discriminant function coefficients, therefore, needs to be developed for the Tropohumult and Gibbsihumox areas on Kauai even though the same terrain factors are investigated.

Examination of aerial photographs showed that Gibbsihumox areas on Oahu occur on hilly and mountainous areas with an average elevation of more than 1,000 feet and a slope greater than 40 percent, while the Tropohumult areas occur on intermediate uplands with an average elevation of less than 700 feet and an average slope of 30 percent (Table X). On the other hand, the Gibbsihumox areas on Kauai occur on intermediate uplands with Tropohumult areas occurring on hilly and mountainous areas.

Discriminant Analysis of Three Great Soil Groups

The discriminant analysis in the previous section included two great soil group areas belonging to two different soil Order. Therefore, the test actually separates two soil Orders--the Ultisol (Tropohumult) and the Oxisol (Gibbsihumox).

In this section discriminant analysis of three great soil groups belonging to one soil Order was performed using the same four terrain factors. These great soil group areas were the Haplustox, Gibbsihumox and Eutrorthox--all classified under the Order Oxisol. Again, the four terrain factors were local relief (RL), average slope (Sm), slope length (SL) and drainage density (Dd).

There were 21, 24, and 20 cells studied in the Haplustox, Gibbsihumox and Eutrorthox areas, respectively. The principal objective of the analysis was to find out whether or not the cells (samples) from each of the three great soil group areas could be distinguished into their corresponding soil areas by means of the discriminant function equation. The procedure was derived from a model of a multivariate normal distribution of observations within groups such that the covariance matrix is the same for all groups. An individual cell (sample) is classified into the group for which the estimated probability density is largest. The equivalent computational procedure followed evaluates the computed linear function corresponding to each of the groups and assigns an individual (cell) to the group for which the value is largest.

The complexity of discriminant analysis increases when more than two populations are involved. Kendall (1961) developed the theory and discussed the method briefly, while Anderson (1958) treated the subject in more detail.

Table XIX shows the coefficients of each of the four terrain factors and the constant used in the discriminant analysis of the three great soil groups.

TABLE XIX. DISCRIMINANT FUNCTION COEFFICIENTS OF FOUR TERRAIN FACTORS AND THE CONSTANT OF THE THREE GREAT SOIL GROUP AREAS

Terrain Factor	Coefficient		
	Haplustox	Eutrorthox	Gibbsihumox
Local relief	0.00309	0.00331	0.00399
Average slope	0.06188	0.03914	0.14295
Slope length	0.00792	0.00852	0.00665
Drainage density	0.84742	0.54948	0.79961
Constant	-10.93545	-8.41681	-13.47597

The discriminant functions, z_1, z_2 and z_3 for the Haplustox, Eutrorthox and Gibbsihumox, respectively, were calculated using the equation:

$$z_i(z_1, z_2, z_3) = \sum_{1}^{m} X_1 C_1 + C_o \qquad (12)$$

where m is the number of variables (terrain factors), X_i is the terrain data, C_i is the coefficient (Table XIX) and C_o is the constant.

For example, to obtain the discriminant function for the Haplustox, the value obtained for the four terrain factors were substituted into Equation 12 to obtain:

$$z_1 = X_1(0.00309) + X_2(0.06188) + X_3(0.00792) + X_4(0.84742) + (-10.93545)$$

where X_1 is the value of local relief; X_2, average slope; X_3, slope length and X_4, drainage density.

The discriminant functions for Eutrorthox, z_2, and for Gibbsihumox, z_3, were calculated similarly to z_1 by substituting the corresponding coefficients and constant.

Each cell was assigned to one of the three great soil groups by computing the probability on the basis of discriminant functions using the equation:

$$P_i = \frac{e^{(z_i - \max z_i)}}{\Sigma\ e^{(z_i - \max z_i}} \qquad (13)$$

P_i = estimated probability (1 or less)

e = exponential function

z_i = sum of z_1, z_2 and z_3

max z_i = largest among z_1, z_2 and z_3

The value of $\Sigma\ e^{(z_i - \max z_i)}$ was obtained for all of the cell members of a group. There were 21, 20 and 24 cell members of Haplustox, Eutrorthox and Gibbsihumox, respectively. The value of $e^{(z_i - \max z_i)}$ can be obtained from the e^x table found in many physical and chemical handbooks.

A cell is assigned into a group having the largest value of probability, P_i. Table XX shows the summary of classification of cells.

TABLE XX. CLASSIFICATION MATRIX OF THE CELLS IN THE THREE GREAT SOIL GROUP AREAS

Soil Group	Total Number of Cell	Number of Cell Classified As		
		Gibbsihumox	Eutrorthox	Haplustox
Gibbsihumox	24	22	0	2
Eutrorthox	20	0	19	1
Haplustox	21	6	7	8

Table XX shows that in the Gibbsihumox area, 22 cells were classified as Gibbsihumox and only two other than this great group. In the Eutrorthox cells all except one were classified as Eutrorthox. Based on these results, it may be concluded that practically all of the cells in Gibbsihumox area have terrain data which characterize this great soil group area. A similar statement can be made about the Eutrorthox area.

In the Haplustox area, however, only 8 out of 21 cells were classified as Haplustox. Seven cells were classified as being in the

Eutrorthox area while 6 cells were classified as being in the Gibbsihumox area. The range of distribution in the Haplustox cells may be due to the common occurrence of Haplustox. As shown in Figure 5, Haplustoxs occur in many areas of Oahu, frequently in close association with soil groups. In Figure 5, for example, the 21 cells selected in the Haplustox areas occur in many parts of the island--Waimanalo area, 3 cells; Kaneohe, 2; Waimea, 6; Kawailoa, 1; Waialua, 5; and Wahiawa, 4. Haplustox cells 1, 2, 3, 4, 5, 6, and 12 were classified as Eutrorthoxs based on the discriminant function coefficients. Close examination of the cell distribution in Figure 5 reveals that these cells are adjacent to or surrounded by Eutrorthox areas. Cells 9, 13, 14 and 16, on the other hand, are adjacent to Gibbsihumoxs and cells 20 and 21 are surrounded by Trophomults.

Effective Terrain Factor in Differentiating the Haplustox, Eutrorthox and Gibbsihumox Areas

The results of the Duncan Multiple Range test in Table XI have shown the effectiveness of local relief (RL), average slope (Sm), slope length (SL) and drainage density (Dd) in differentiating the Haplustox, Eutrorthox and Gibbsihumox areas. However, the test failed to indicate which of the four terrain factors was the single most important quantitative terrain factor in segregating the three great soil groups.

Multiple discriminant analysis in a stepwise manner, a form of multivariate analysis, therefore, was utilized to determine which of the variables or terrain factors was most effective in discriminating the several groups. The principle and its application of this so-called "Stepwise Discriminant Analysis" are discussed by Anderson (1958) and Rao (1952).

The results of the stepwise discriminant analysis showed that average slope was the most effective terrain factor that can be used to differentiate the Haplustox, Eutrorthox and Gibbsihumox areas. Drainage density was next most effective, followed by slope length and finally local relief. Table XXI shows the list of the four terrain factors and the F-values. The list is from the most effective to least effective in terms of segregating the three great soil group areas studied.

TABLE XXI. TERRAIN FACTORS (FROM MOST EFFECTIVE LEAST EFFECTIVE) AND THE COMPUTED F-VALUES BASED ON 2 AND 62 DEGREES OF FREEDOM, RESPECTIVELY

Terrain Factor	F value
Average slope	39.27
Drainage density	33.85
Slope length	21.59
Local relief	14.42

The result of the classification of cells obtained from stepwise discriminant analysis was similar to the result obtained from the discriminant analysis presented in Table XX.

Correlation Between Terrain Factors on Oahu

The computation of correlation coefficient involving large number of variables was shown by Krumbein and Graybill (1965).

Table XXII shows the value of correlation coefficient between two terrain factors. The significance was based on r values based on 151 degrees of freedom. For convenience, a graphical representation of correlation between two terrain factors is presented in Table XXIII.

The correlation matrix (Table XXIII) shows that there is a significant correlation between the different terrain factors, with the exception of slope length curvature. The relationship between slope length (SL) and the other terrain factors shows negative correlation because slope length decreases when factors such as slope (Sm) and local relief (RL) increase. Because slope length and slope width curvature (Swc) are positively correlated with each other, the same reason can be used to explain the negative correlation between slope width curvature and the other terrain factors.

Results Obtained on Kauai

General

Six soil association areas were selected for investigation on Kauai (Table II). Figure 6 shows the distribution of the 169 test cells studied in the six soil association areas. The ten terrain factors measured in each cell were the same ten terrain factors used in the study of great soil group areas on Oahu (Table III).

TABLE XXII. VALUES OF CORRELATION COEFFICIENT BETWEEN TWO TERRAIN FACTORS BASED ON 153 OBSERVATIONS ON OAHU

Terrain Factor Combination	Correlation Coefficient
Ea-RL	0.236*
Ea-Sm	0.433*
Ea-SL	-0.305*
Ea-Slc	0.211*
Ea-Swc	-0.327*
Ea-TL	0.300*
Ea-Dd	0.284*
Ea-Rn	0.460*
Ea-Gd	0.332*
RL-Sm	0.656*
RL-SL	-0.484*
RL-Slc	0.032
RL-Swc	-0.288*
RL-TL	0.513*
RL-Dd	0.528*
RL-Rn	0.640*
RL-Gd	0.550*
Sm-SL	-0.589*
Sm-Slc	0.077
Sm-Swc	-0.430*
Sm-TL	0.659*
Sm-Dd	0.660*
Sm-Rn	0.681*
Sm-Gd	0.626*

TABLE XXII. (CONTINUED) VALUES OF CORRELATION COEFFICIENT BETWEEN TWO TERRAIN FACTORS BASED ON 153 OBSERVATIONS ON OAHU

Terrain Factor Combination	Correlation Coefficient
SL-Slc	-0.039
SL-Swc	0.276*
SL-TL	-0.515*
SL-Dd	-0.520*
SL-Rn	-0.551*
SL-Gd	-0.533*
Slc-Swc	-0.095
Slc-TL	-0.018
Slc-Dd	-0.006
Slc-Rn	0.032
Slc-Gd	0.064
Swc-TL	-0.437*
Swc-Dd	-0.434*
Swc-Rn	-0.402*
Swc-Gd	-0.332*
TL-Dd	0.962*
TL-Rn	0.715*
TL-Gd	0.489*
Dd-Rn	0.743*
Dd-Gd	0.485*
Rn-Gd	0.694*

*Correlation coefficient highly significant.

Ea=average elevation (feet), RL=local relief (feet), Sm=average slope (percent), SL=slope length (feet), Slc=slope length curvature (ratio), Swc=slope width curvature (degree), TL=land texture ratio (mile^{-1}), Dd=drainage density (mile/square mile), Rn=ruggedness number (feet/mile), Gd=mean gully depth (feet).

TABLE XXIII. CORRELATION BETWEEN TWO TERRAIN FACTORS BASED ON 153 OBSERVATIONS ON OAHU

Terrain Factor*	Ea	RL	Sm	SL	Slc	Swc	TL	Dd	Rn	Gd
Ea	1.00									
RL	0.24	1.00								
Sm	0.43	0.65	1.00							
SL	-0.31	-0.48	-0.59	1.00						
Slc	0.21	0.03	0.08	-0.04	1.00					
Swc	-0.33	-0.29	-0.43	0.28	-0.09	1.00				
TL	0.30	0.51	0.66	-0.51	-0.02	-0.44	1.00			
Dd	0.28	0.53	0.66	-0.52	-0.01	-0.43	0.96	1.00		
Rn	0.46	0.64	0.68	-0.55	0.03	-0.40	0.71	0.74	1.00	
Gd	0.33	0.55	0.62	-0.53	0.06	-0.33	0.49	0.48	0.69	1.00

*The intersecting square of two terrain factors shows the correlation coefficient between the two factors.

df = n-2 = 153-2 = 151

$P_{0.05}$, r = 0.159; $P_{0.01}$, r = 0.209

The data for each terrain factor were tested by analysis of variance to determine whether or not the mean values obtained from six soil association areas were significantly different. Analysis of variance model used is shown in Table IX. Terrain factors which showed significant difference were usbjected to Multiple Range Test to determine which of the soil association comparisons were significant and to determine which of the terrain factors could be used to distinguish between the two soil association areas.

The numerical groupings of 169 cells on the six soil association areas are discussed, and the results of the classification of 108 test cells selected from presumably unknown areas on Kauai are transformed to map and compared with the soil maps produced by SCS for the same area.

Efficiency of Various Terrain Factors

Table XXIV shows the mean values of ten terrain factors obtained from the six soil association areas. All F-values except for slope length curvature (Slc) were significant at the 99 percent level of significance. Results of analysis of variance are shown in Appendix D. Slope length curvature data were not subjected to Multiple Range Test since there was no significant difference among the six means.

The terrain factors selected for investigation indicated a wide range of effectiveness. Tables XXV and XXVI shows the efficiency of the various terrain factors at the 95 and 99 percent significance levels, respectively. It was noted that 14 out of 15 possible combinations of six soil association areas could be separated by

TABLE XXIV. MEAN VALUES OF TERRAIN DATA OBTAINED FROM SIX SOIL ASSOCIATIONS ON KAUAI

Soil Assoc.[b]	Terrain Factor[a]									
	Ea	RL	Sm	SL	Slc	Swc	TL	Dd	Rn	Gd
KP	611.70	174.00	12.29	1817.71	0.89	49.28	5.22	9.83	1793.24	105.08
LP	299.20	100.00	7.33	2146.98	0.95	57.84	4.70	9.50	1077.66	58.65
MW	861.97	578.05	31.06	1718.36	0.94	58.16	4.88	9.08	5475.27	310.96
WK	158.64	88.85	4.50	1412.45	1.25	66.49	3.01	5.77	560.73	39.77
MK	2730.95	453.57	30.73	704.09	1.12	47.68	6.33	13.35	6231.26	231.58
WA	4115.55	265.00	36.87	651.39	0.99	33.95	8.09	18.31	4669.60	182.33
F-value[c]	379.30	39.18	55.23	103.41	1.88ns	12.28	24.92	39.38	121.50	30.96

[a] Ea=average elevation, RL=local relief, Sm=average slope, SL=slope length, Slc=slope curvature, Swc=slope width curvature, TL=land texture ratio, Dd=drainage density, Rn=ruggedness number, and Gd=gully depth.

[b] KP=Kapaa-Pooku-Halii-Makapili soils, LP=Lihue-Puhi soils, MW=Makaweli-Waiawa-Niu soils, WK=Waikoma-Kalihi-Koloa soils, MK=Mahana-Kokee-Paaiki soils, WA=Waialeale-Alakai soils.

[c] All F-values except that of Slc were significant at 99 percent level of significance.

TABLE XXV. SIGNIFICANT TERRAIN FACTORS WHEN COMPARING SOIL ASSOCIATIONS ON KAUAI (95 PERCENT LEVEL OF SIGNIFICANCE)

Soil	Terrain Factor									
Assoc.	Ea	RL	Sm	SL	Slc	Swc	TL	Dd	Rn	Gd
KP-LP	x		x	x		x				
KP-MW	x	x	x			x				x
KP-WK	x		x	x		x	x	x		
KP-MK	x	x	x	x			x	x		x
KP-WA	x		x	x		x	x	x	x	x
LP-MW	x	x	x	x						x
LP-WK				x			x	x		
LP-MK	x	x	x	x		x	x	x		x
LP-WA	x	x	x	x		x	x	x	x	x
MW-WK	x	x	x	x			x	x		x
MW-MK	x	x		x		x	x	x		x
MW-WA	x	x	x	x		x	x	x	x	x
WK-MK	x	x	x	x		x	x	x		x
WK-WA	x	x	x	x		x	x	x	x	x
MK-WA	x	x	x			x	x	x	x	
Total	14	11	13	13	0	11	12	12	5	11
Percent	93	73	86	86	0	73	80	80	33	73

TABLE XXVI. SIGNIFICANT TERRAIN FACTORS WHEN COMPARING SOIL ASSOCIATIONS ON KAUAI (99 PERCENT LEVEL OF SIGNIFICANCE)

Soil	Terrain Factor									
Assoc.	Ea	RL	Sm	SL	Slc	Swc	TL	Dd	Rn	Gd
KP-LP	x			x						
KP-MW		x	x							x
KP-WK	x			x		x	x	x		
KP-MK	x	x	x	x			x	x		x
KP-WA	x		x	x		x	x	x	x	x
LP-MW	x	x	x	x						x
LP-WK				x			x	x		
LP-MK	x	x	x	x		x	x	x		x
LP-WA	x	x	x	x		x	x	x	x	x
MW-WK	x	x	x	x			x	x		x
MW-MK	x	x		x		x	x	x		x
MW-WA	x	x		x		x	x	x	x	x
WK-MK	x	x	x	x		x	x	x		x
WK-WA	x	x	x	x		x	x	x	x	x
MK-WA	x	x				x	x	x	x	
Total	13	11	9	13	0	9	12	12	5	11
Percent	86	73	60	86	0	60	80	80	33	73

average elevation (Ea). Average slope (Sm) followed the rank of effectiveness in distinguishing between two soil association areas. At the 99 percent level of significance average slope was not as effective.

Based on Table XXV, five terrain factors appeared significant in separating the various combinations of soil association areas on Kauai. These terrain factors, based on 95 percent level of significance, were:

1. Average elevation (Ea)
2. Average slope (Sm)
3. Slope length (SL)
4. Land texture ratio (TL)
5. Drainage density (Dd)

The four most effective terrain factors based on 99 percent level of significance were as follows:

1. Average elevation (Ea)
2. Slope length (SL)
3. Land texture ratio (TL)
4. Drainage density (Dd)

While average elevation appeared the most effective terrain factor in distinguishing two soil association areas on Kauai, the same terrain factor was not found to be effective in separating two great soil group areas on Oahu. The high degree of effectiveness of average elevation on Kauai may be due to the fact that soil association is a group of soils regularly occurring in similar geographical location. In mapping the area for soil association, attention is given to geographical association of soils. Great soil group is a result of grouping soil series and profile characteristics rather than terrain receives careful consideration.

Slope length curvature (Slc) was not effective in differentiating between any of the soil associations.

Distribution of Soil Association Areas by Terrain Quantification Factors

The basic objective of this section was to determine whether or not quantitative terrain factors could be used to distinguish the different soil association areas. The results have shown that the six soil association areas have significantly different terrain factors which can be measured from aerial photographs and/or 1:24,000 scale topographic maps.

All of the 15 possible combinations of soil association areas have at least three terrain factors which can be used to segregate the two areas (Table XXVII).

Table XXVII indicates that each of the 15 soil association combinations has three to nine distinguishing terrain factors. The study showed that differences in several aspects of topography of the soil association areas can be characterized by a number of quantitative terrain factors. Plates 7 to 11, Appendix E show stereograms of aerial photographs of the soil association areas.

Correlation Between Terrain Factors on Kauai

The correlation matrix (Table XXVIII) shows, as in the study on Oahu (Table XXIII), that there is a significant correlation between the different terrain factors, with the exception of the slope length curvature (Slc). There were, however, some minor differences.

TABLE XXVII. SUMMARY OF SIGNIFICANT DIFFERENCE BETWEEN KAUAI SOIL ASSOCIATION AREAS. DATA ARE BASED ON DUNCAN MULTIPLE RANGE TEST, 95 PERCENT SIGNIFICANT. TERRAIN FACTORS WHICH CAN BE USED TO DISTINGUISH BETWEEN TWO SOIL ASSOCIATION AREAS ARE LISTED IN THE INTERSECTING SQUARE.

KP						
LP	E_a S_{wc} S_m S_L					
MW	E_a S_{wc} R_L G_d S_m	E_a S_L R_L G_d S_m				
WK	E_a S_{wc} S_m T_L S_L D_d	S_L T_L D_d	E_a T_L R_L D_d S_m G_d S_L			
MK	E_a T_L R_L D_d S_m G_d S_L	E_a S_{wc} R_L T_L S_m D_d S_L G_d	E_a T_L R_L D_d S_L G_d S_{wc}	E_a S_{wc} R_L T_L S_m D_d S_L G_d		
WA	E_a T_L S_m D_d S_L R_n S_{wc} G_d	E_a S_{wc} R_L T_L S_m G_d D_d S_L R_n	E_a S_{wc} R_L T_L S_m G_d D_d S_L R_n	E_a S_{wc} R_L G_d T_L S_m D_d S_L R_n	E_a T_L R_L D_d S_m R_n S_{wc}	
SOIL ASSOC.	**KP**	**LP**	**MW**	**WK**	**MK**	**WA**

TABLE XXVIII. MATRIX OF LINEAR CORRELATION FOR TEN TERRAIN FACTORS BASED ON 169 OBSERVATIONS ON KAUAI

Terrain Factor*	Ea	RL	Sm	SL	Slc	Swc	TL	Dd	Rn	Gd
Ea	1.00									
RL	0.23	1.00								
Sm	0.61	0.72	1.00							
SL	-0.77	-0.24	-0.55	1.00						
Slc	0.12	-0.05	-0.05	-0.08	1.00					
Swc	-0.44	-0.04	-0.37	0.43	0.03	1.00				
TL	0.57	0.25	0.57	-0.50	-0.05	-0.55	1.00			
Dd	0.67	0.20	0.56	-0.57	-0.01	-0.54	0.91	1.00		
Rn	0.20	0.16	0.16	-0.18	-0.07	-0.19	0.20	0.18	1.00	
Gd	0.27	0.75	0.83	-0.25	-0.06	-0.16	0.29	0.24	0.04	1.00

*The intersecting square of two terrain factors shows the correlation between the two factors.

df = n-2 = 169-2 = 167

$P_{0.05}$, r = 0.159; $P_{0.01}$, r = 0.209

The ruggedness number (Rn), for example, was highly correlated with other terrain factors on Oahu, with the exception of slope length curvature, but only significant at the 95 percent level on Kauai. Similarly, Rn on Kauai was not correlated with slope length curvature. Average elevation (Ea) and slope length curvature were highly correlated on Oahu but these terrain factors showed no significant correlation on Kauai. Finally, although there was a significant relationship between slope width curvature (Swc) and local relief (RL) on Oahu, there was no such relationship on Kauai.

NUMERICAL CLASSIFICATION OF CELLS ON KAUAI

Electronic computers have contributed much to the development of quantitative numerical methods for purposes of classification. Grigal and Arneman (1969) applied multivariate statistical procedures of numerical groupings of 40 Minnesota forest soils based on properties which can be measured in the field and the laboratory. The basic objective in numerical classification or grouping is to show the interrelationships within a similarity coefficient matrix. This may be accomplished by arranging the variables in a hierarchical dendritic network or dendrogram in which the different variables or samples are grouped or clustered so that their interrelationships are shown with greatest simplicity.

Numerical classification as defined in this paper is a procedure which involved computing statistical coefficients and estimating the similarity of each test cell to every other cell in the study. It is a simple form of correlation analysis, a method searching for relationships in a large symmetrical matrix. It is a straightforward, logical, pair by pair comparison between samples, objects or variables.

The computation of correlation coefficients for all possible comparisons of the cells on the basis of selected terrain factors yield a matrix table of similarity coefficients among cells which indicates the quantitative similarity of each cell to every other cell. A clustering method then summarizes all the similarities among the cells which can be displayed as dendrogram or for purposes of this paper transformed into map.

In numerical classification, all characters are usually treated as of equal importance giving them equal weighting in the classification. Sokai and Sneath (1963) gave several reasons for equal weighting of characters. First, equal weighting results in a general classification which can be of general use to many disciplines for many purposes. Being general, there are some limitations for any specific purpose. However, if a special purpose classification is desired, it could be made so by equal weighting of a special purpose group of characters. Second, it is difficult to be completely objective in assigning differential weights to characters and if such a thing is done, exact rules for assigning weights should be stated. Third, equal weighting appears automatically during the mathematical computations of numerical classification.

General Procedures of Numerical Classification

This study includes five terrain factors quantified to varying sizes, numbers and measurements. In order to remove this variation all data were standardized using the transformation equation (Equation 2). Raw data matrix (Table XXIX) was standardized column by column in order to give equal weight to each of the terrain factors which were measured in quite different sized units. The standardized data are shown in Table XXX. The data presented in Table XXIX were from ten of the 108 cells numerically classified on Kauai and are shown only as examples.

The standarized data of the five terrain factors (Table XXX) were combined and from this value, the mean and the standard deviation of each cell were computed.

TABLE XXIX. TERRAIN FACTORS FROM TEN CELLS (BEFORE STANDARDIZATION)

	Terrain Factor*				
Cell	1	2	3	4	5
1	380.00	120.00	18.30	1411.48	3.56
2	435.00	70.00	5.40	2138.35	2.12
3	420.00	40.00	4.80	1200.00	2.00
4	360.00	80.00	9.60	1580.00	2.81
5	200.00	240.00	31.94	720.00	3.35
6	160.00	240.00	25.60	1200.00	2.68
7	160.00	240.00	40.44	1720.00	1.06
8	460.00	360.00	29.90	360.00	2.25
9	190.00	340.00	24.40	500.00	2.25
10	290.00	540.00	25.34	500.00	2.81

*1-average elevation, 2-local relief, 3-average slope, 4-slope length, 5-land texture ratio.

TABLE XXX. TERRAIN FACTORS FROM TEN CELLS (AFTER STANDARDIZATION)

	Terrain Factor						
Cell	1	2	3	4	5	Mean	Standard Deviation
1	5.27	4.65	5.31	5.21	6.15	5.31	0.48
2	5.76	4.32	4.17	6.42	4.74	5.08	0.86
3	5.63	4.12	4.11	4.85	4.62	4.66	0.56
4	5.09	4.38	4.54	5.49	5.41	4.98	0.44
5	3.67	5.44	6.52	4.05	5.94	5.12	1.09
6	3.32	5.44	5.96	4.85	5.29	4.97	0.89
7	3.32	5.44	7.28	5.72	3.70	5.09	1.44
8	5.98	6.23	6.34	3.46	4.86	5.37	1.09
9	3.58	6.10	5.85	3.96	4.86	4.81	1.05
10	4.47	7.43	5.94	3.69	5.41	5.38	1.28

Using the familiar product-moment formula, the correlation coefficients for the ten cells were calculated. There are $(K^2 - K)/2$ number of combinations (K = number of cells). The correlation matrix is shown in Table XXXI.

The final step in numerical classification involves clustering of cells, employing some form of similarity coefficient such as correlation coefficients to bring the most similar cells adjacent to each other. The method used in this particular program was the unweighted average linkage method (Harbaugh and Merriam, 1968). The method involves clustering mutually similar entities. The clusters are built up around centers of the most similar pairs of entities (cells). A candidate cell for entry to a cluster is admitted at a similarity level equal to the average similarity between the candidate and the existing members of the cluster. As the similarity levels are lowered the remaining entities join one or another of the clusters, individual clusters ultimately join, and finally all entities are included in one large cluster; that is, one cell member group, the number of groups being equivalent to the number of cells. By this method, each entity is given an equal influence throughout the clustering process. Other clustering methods was discussed in detailed by Sokal and Sneath (1963).

Numerical Grouping of 169 Test Cells

A total of 169 cells from six soil association areas on Kauai with ten terrain factors (Table II) was numerically classified to determine the relationship of such groupings with the random location of the test cells in the soil association areas. All ten terrain factors were considered in clustering the cells.

TABLE XXXI. CORRELATION MATRIX

	1	2	3	4	5	6	7	8	9	10
1	1.00									
2	0.02	1.00								
3	0.19	0.75	1.00							
4	0.65	0.75	0.59	1.00						
5.	0.24	-0.88	-0.84	-0.47	1.00					
6.	0.01	-0.67	-0.96	-0.40	0.87	1.00				
7.	-0.40	-0.34	-0.72	-0.50	0.49	0.73	1.00			
8.	-0.31	-0.73	-0.24	-0.84	0.39	0.08	0.10	1.00		
9.	-0.25	-0.93	-0.90	-0.81	0.85	0.80	0.54	0.60	1.00	
10.	-0.36	-0.89	-0.72	-0.84	0.65	0.56	0.26	0.70	0.92	1.00

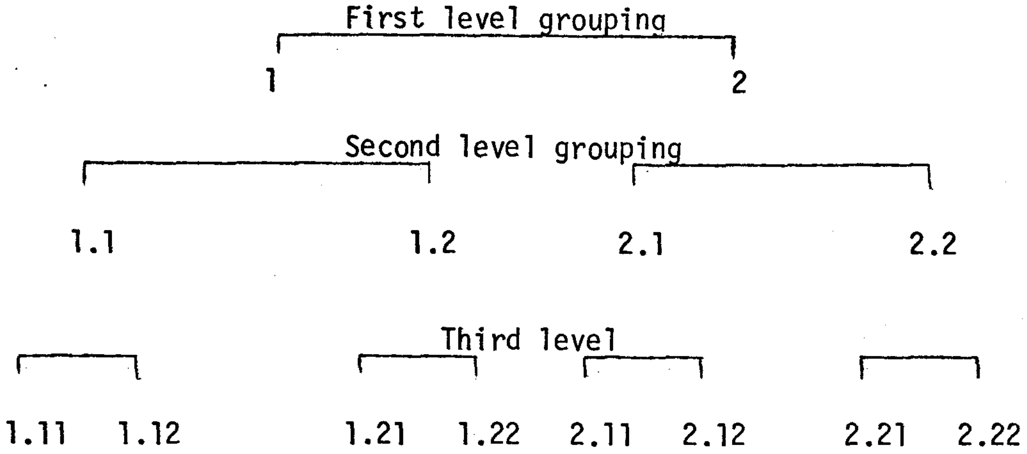


FIG. 13. LEVELS OF GROUPINGS OF 169 CELLS ON KAUAI USING TEN TERRAIN FACTORS

The first level grouping (Figure 13) indicates that the 169 cells can be classified into two distinct groups (Table XXXII). Group 1 is composed of soil association areas KP, LP and WK, while Group 2 is composed of areas MK and WA. Only the area MW appears to be somewhat equally divided between the two groups.

The data in Table XXXIII indicate that the two groups represent areas of highly contrasting terrain features. Group 1 cells represent nearly level to level areas with an average elevation of less than 500 feet above sea level. Group 2 area is a rough, highly dissected area with an average elevation higher than 2000 feet above sea level. Group 2 area is made up principally of MK (Mahana-Kokee-Paaiki soils) and WA (Waialeale-Alakai soil) cells. Both of these soil associations occur on moderately to very steep upland on western part of Kauai.

TABLE XXXII. FIRST LEVEL GROUPING OF 169 CELLS ON KAUAI

Soil Association Area	Number of Cell	Number of Cells Classified As	
		Group 1	Group 2
KP	30	29	1
LP	25	25	0
MW	35	16	19
WK	14	14	0
MK	45	0	45
WA	20	0	20
Total	169	84	85

TABLE XXXIII. MEAN AND STANDARD ERROR OBTAINED FOR GROUPS 1 AND 2

Terrain Factor	Group 1 Mean	Group 1 Standard Error	Group 2 Mean	Group 2 Standard Error
Ea	473.22	37.79	2631.45	131.21
RL	169.64	13.71	478.31	27.15
Sm	11.07	0.86	34.03	1.14
SL	1868.76	47.39	892.45	49.17
Slc	0.99	0.05	1.04	0.07
Swc	57.68	1.96	45.53	1.36
TL	4.44	0.17	6.59	0.18
Dd	8.55	0.36	13.89	0.43
Rn	1495.60	117.19	10944.77	102.20
Gd	99.88	8.71	79.83	14.91

In the second level grouping, Group 1 and Group 2 were subdivided into two subgroups each (Figure 13). Table XXXIV shows the number of cells from each of the six soil association areas assigned to the four subgroups.

The principal objective of subjecting the 169 cells to numerical classification was to determine whether or not the groupings established by means of similarity coefficients will agree with the boundaries of the soil association areas established by SCS. The second and third level groupings did not completely agree with the established soil association areas from which the 169 cells were selected. When such grouping was transformed to a map, it did not coincide with the boundary lines drawn for either the major soil series or the soil associations. However, the result of groupings indicated that the MK and WA soil association areas were fairly well segregated from other soil association areas.

The random location and great distance between cells (Figure 6) may account for lack of coincidence between the numerical groupings and soil association areas. For this reason, it was decided to establish the cells in grid over the whole area and subject the data to numerical grouping. Consequently, another area on Kauai was selected. Results of this grouping in comparison with the soil map produced for the same area by SCS is discussed in the succeeding portion of this paper.

Numerical Classification of 108 Cells on Eastern Kauai

General. One hundred eight cells were established in a grid system in a 27-square mile area in eastern portion of topographic and

TABLE XXXIV. SECOND LEVEL GROUPING OF 169 CELLS ON KAUAI

Soil Association Area	Number of Cell	Number of Cell Classified As Subgroup 1.1	1.2	2.1	2,2
KP	30	21	8	1	0
LP	25	8	17	0	0
MW	35	13	3	19	0
WK	14	3	11	0	0
MK	45	0	0	19	26
WA	20	0	0	1	19
Total	169	45	39	40	45

aerial photographic maps of Kauai for numerical grouping (Figure 14). Five terrain factors were measured on each of the 108 cells. These were average elevation (Ea), local relief (RL), average slope (Sm), slope length (SL) and land texture ratio (TL). As mentioned previously, the decision to use these five terrain factors was based on two important consideration: (1) high efficiency of these factors in differentiating soil associations and (2) ability to measure these factors on topographic map and/or aerial photographs.

The cell data were numerically classified for grouping similar cells and for comparing the different levels of groupings with the soil maps produced by the Soil Conservation Service or SCS, USDA, for the same area. The objective was to determine whether or not the numerical groupings would support or agree with the boundaries drawn for the area by soil survey. If the five terrain factors mentioned above were related to the soils as it were found in previous tests, then the map compiled on the basis of cell grouping should be similar or nearly similar to the existing soil map. Visual comparison was made between the two maps but no attempt was made to quantify any relationship. Only three levels of groupings were considered and the groupings were compared with the data in the soil maps. The first level grouping was composed of 2 groups, second level grouping by 4 groups and third level grouping by 8 groups.

First Level Grouping and Physiographic Division of the Area

In the first level grouping, the 108 cells were divided into two groups--the first group consisted of 56 cells while the second group consisted of 52 cells. Table XXXV indicates that these groups

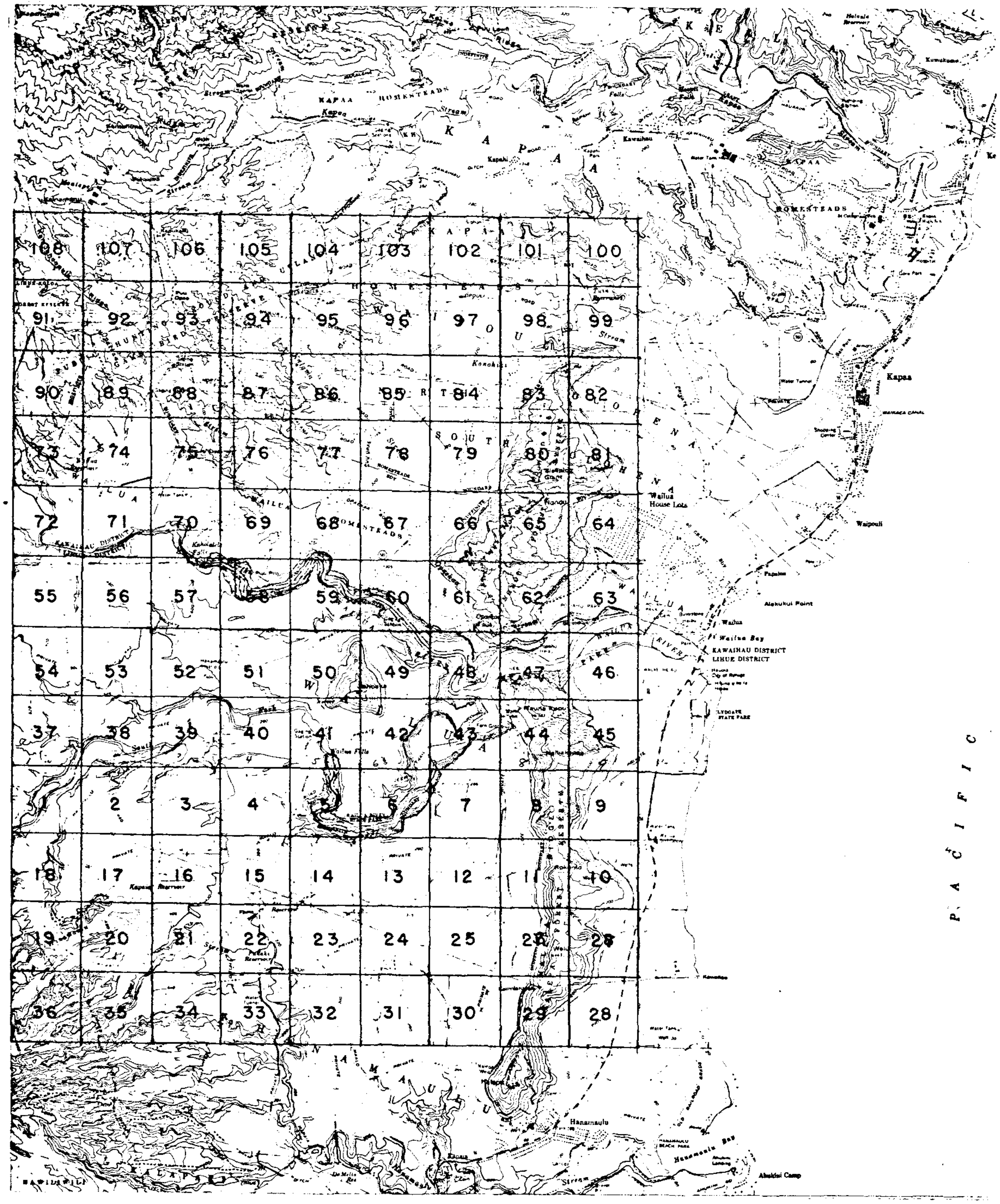


FIG. 14. A 27-SQUARE MILE AREA IN EASTERN PART OF KAUAI SHOWING THE 108 CELLS ESTABLISHED IN 0.5-MILE GRIDS FOR NUMERICAL CLASSIFICATION

TABLE XXXV. MEAN AND STANDARD ERROR OF THE FIRST LEVEL GROUPING OF 108 CELLS ON KAUAI

Terrain Factor	Group 1		Group 2	
	Mean	Standard Error	Mean	Standard Error
Ea	359.10	12.32	476.70	31.75
RL	119.80	14.67	358.90	29.42
Sm	11.50	1.35	24.80	1.73
SL	1605.40	71.16	710.50	45.24
TL	2.45	0.19	3.46	0.12
Number of cell	56		52	

Ea=average elevation (feet), RL=local relief (feet)

Sm=average slope (percent), SL=slope length (feet)

TL=land texture ratio (mile^{-1})

represent two contrasting areas in terms of the terrain factors considered. Group 1 may be described as nearly level to moderately sloping area while Group 2 may be described as moderately to very steeply sloping upland. Furthermore, Group 1 area has elevation ranging from 150 to 440 feet above sea level while Group 2 has elevation ranging from 150 to almost 1000 feet above sea level. The length of slope in Group 1 area is also much longer than in Group 2. Group 2, on the other hand, has a land texture ratio greater than that of Group 1. In other words, Group 2 has more rugged topography than Group 1.

Figure 15 shows the first level grouping of the cells with the boundaries of the major physiographic division of the area printed on a transparent overlay. The major physiographic division of the area was prepared simply by studying the contours on topographic map.

Figure 15 indicates that the first level grouping corresponds closely with the major physiographic data of the area. Group 2 cells coincide with hilly and mountainous areas with the exception of cell number 38, and Group 1 corresponds very closely with the level areas established by examination of contour lines on the topographic map.

The results of visual comparison suggest that numerical grouping of cells, using the five quantitative terrain factors, can be used successfully in separating a region into broad physiographic areas. However, such division can be done qualitatively by examining topographic maps although no quantitative data is obtained. In fairly level region where there are no sharp breaks in topography

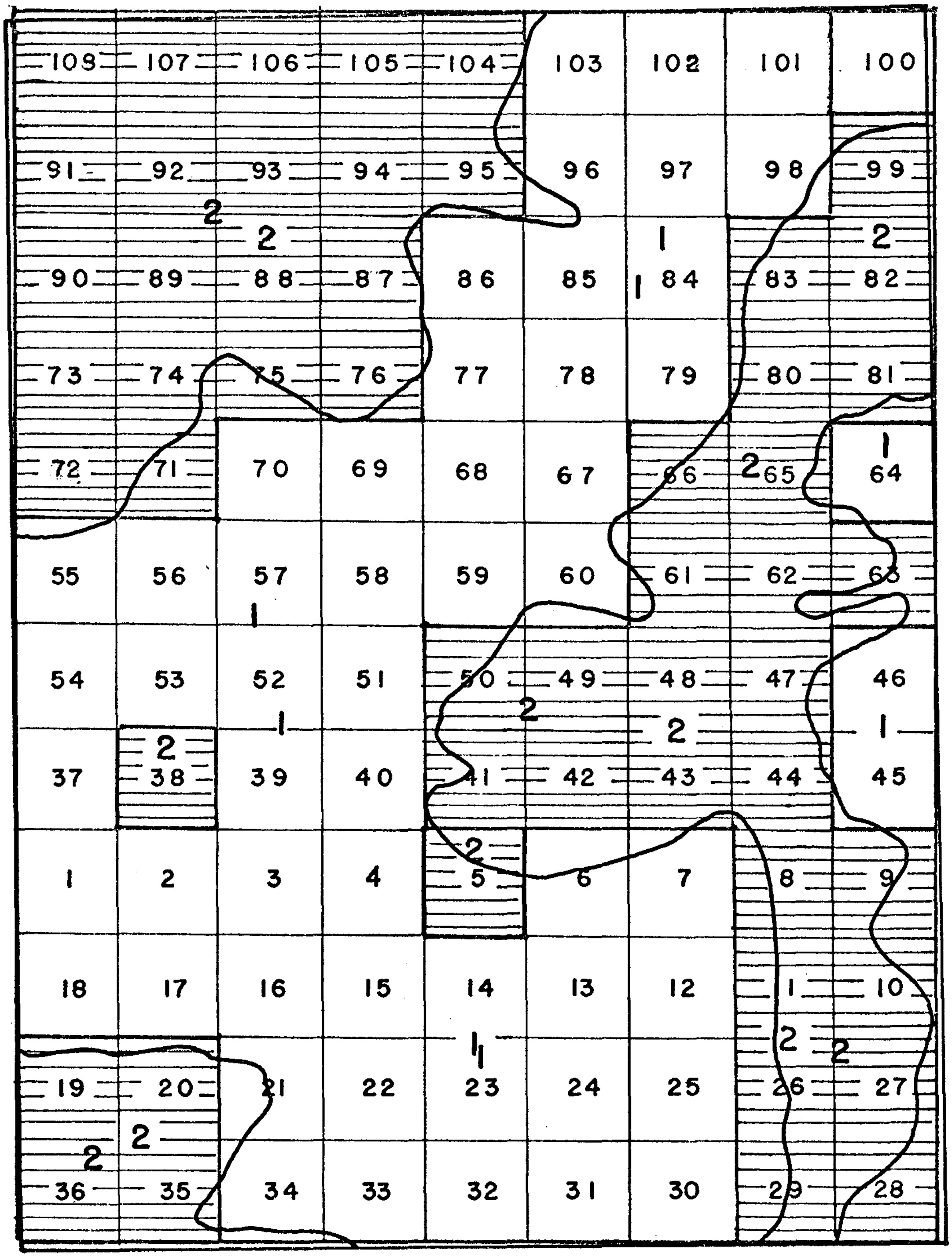
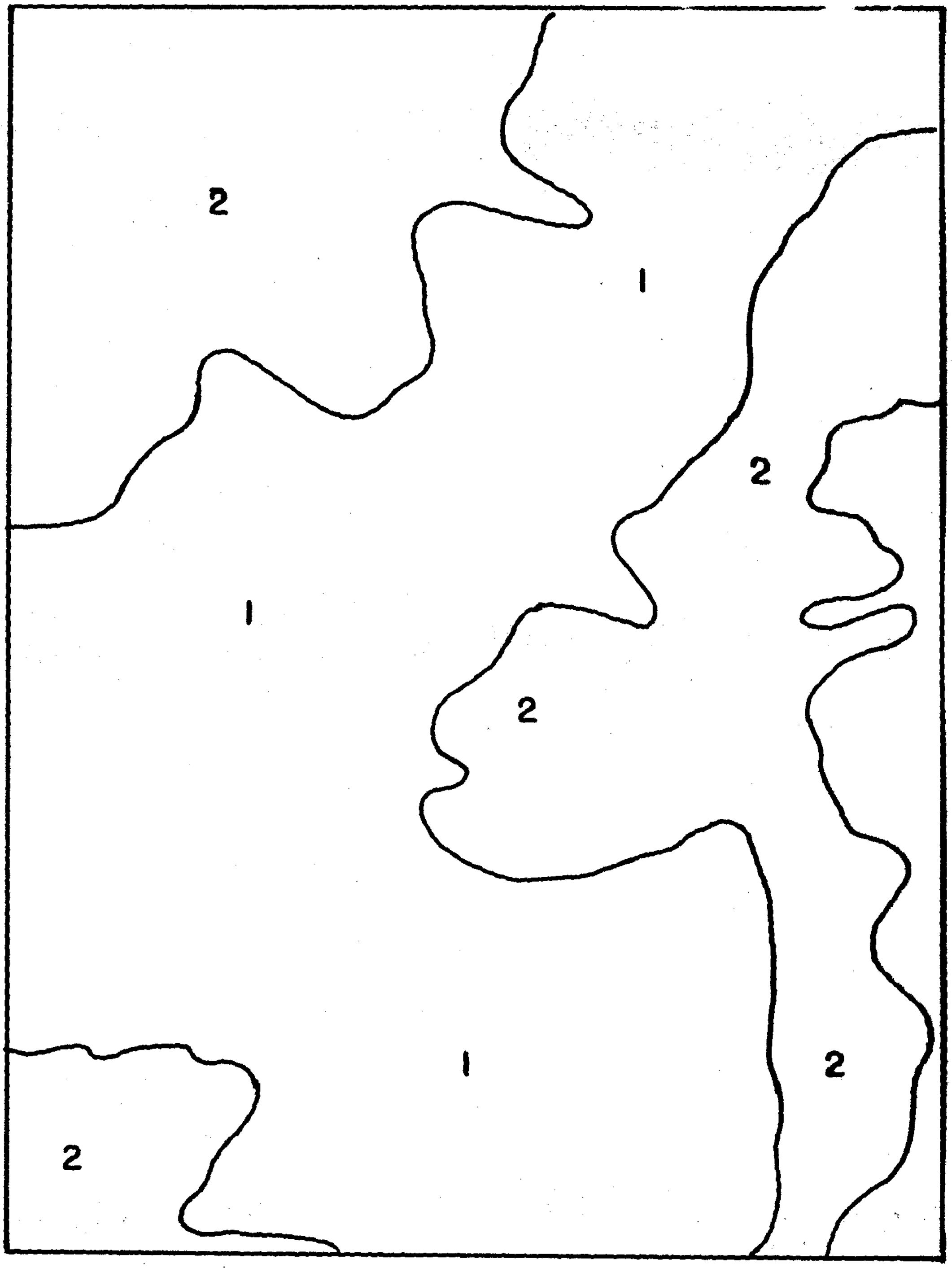


FIG. 15. FIRST LEVEL GROUPING AND MAJOR PHYSIOGRAPHIC DIVISION (TRANSPARENT OVERLAY). 1=LEVEL AREA; 2= STEEP UPLAND, HILLY AND MOUNTAINOUS AREAS.


2
1
2
1
2
1
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2

/ : /

(e.g., hills, mountains, gullies), the numerical grouping technique may have the advantage over mere examination of topographic map. In such level areas, contour lines appear uniform and without measuring and quantifying them it is quite difficult or almost impossible to make separations over the whole region.

Second Level Grouping of 108 Cells

The second level grouping was made up of four groups resulting from the subdivision of Groups 1 and 2 of the first level into two subgroups each. Groups 1.1 and 1.2 are subgroups of Group 1 while Group 2.1 and 2.2 were subgroups of Group 2. The mean and standard error of the four groups in the second level groupings are presented in Table XXXVI. Figure 16 shows the particular cells which were grouped into Group 1.1, 1.2, 2.1 and 2.2.

Two kinds of soil maps (Soil Associations and Soil Orders) of the area were compiled and compared with the second level grouping. As shown in Figure 16, the soil maps were prepared on transparent overlays and superimposed on the numerical grouping map. The same figure shows the comparison between soil association map and second level grouping, and the results show good correspondence between the KP soils and Group 1.1, LP soils and Group 1.2 and RM area and Groups 2.1 and 2.2. It will be shown later although both of these latter groups represent the RM area, they actually differentiate into other groups at the lower categories.

A map showing the soil Orders was prepared based on the data provided by the Soil Conservation Service classification, USDA. Based on the soil series maps, there were three soil Orders in the

TABLE XXXVI. MEAN AND STANDARD ERROR OF THE SECOND LEVEL GROUPING OF 108 CELLS ON KAUAI

	Group 1.1		Group 1.2		Group 2.1		Group 2.2	
Terrain Factor	Mean	Standard Error	Mean	Standard Error	Mean	Standard Error	Mean	Standard Error
Ea	349.60	11.08	326.40	15.78	386.10	33.33	574.50	29.40
RL	111.00	15.92	123.70	14.90	496.80	37.95	209.90	19.80
Sm	12.90	1.34	10.90	1.44	24.80	1.92	24.70	1.72
SL	1421.00	70.87	1685.70	74.42	705.10	47.20	716.20	43.60
TL	3.54	0.16	1.98	0.05	2.76	0.13	4.22	0.14
Number of cell	17		39		27		25	

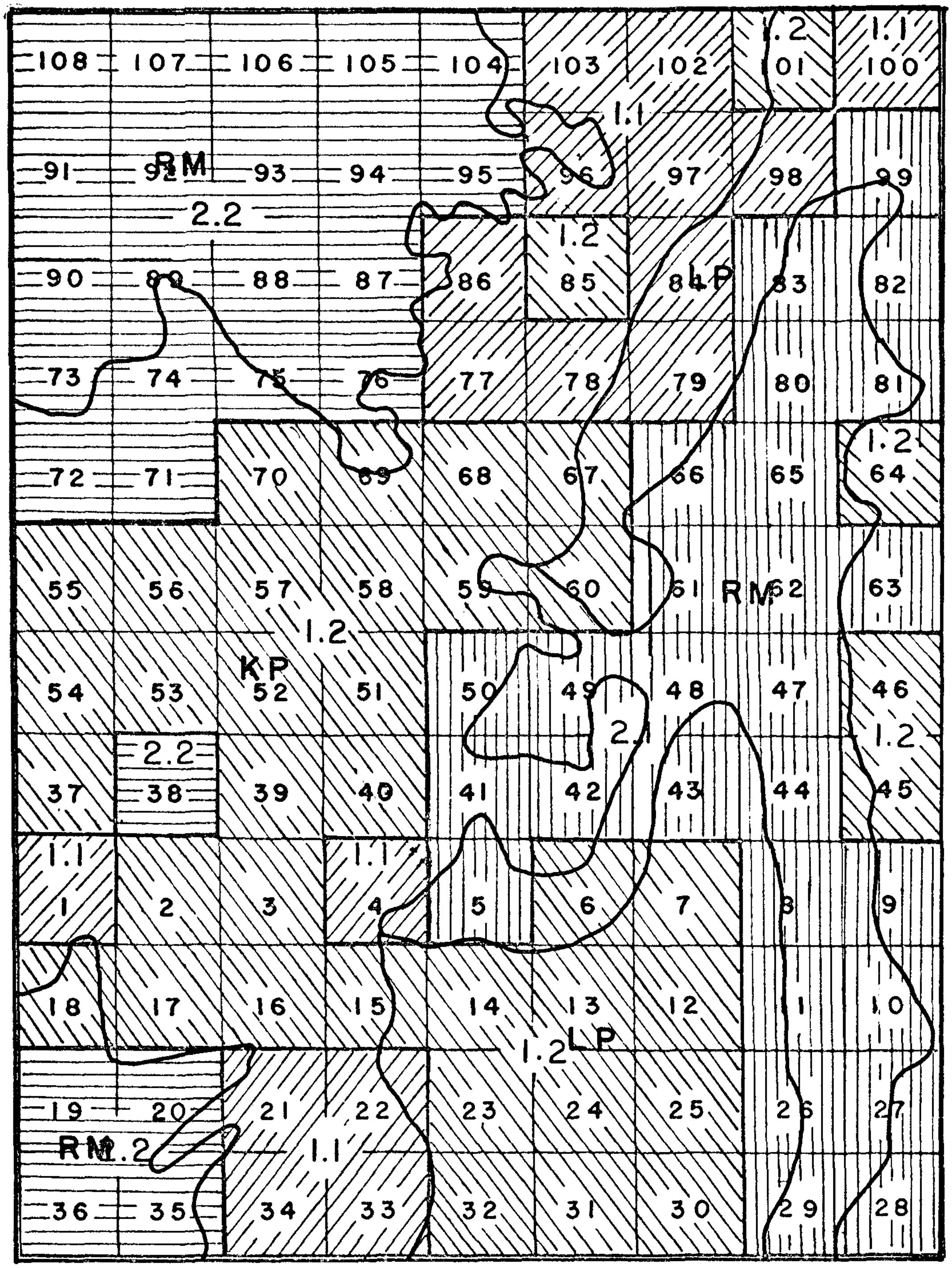


FIG. 16. SECOND LEVEL GROUPING AND SOIL ASSOCIATION MAP (TRANSPARENT OVERLAY) LP=LIHUE-PUHI SOILS; KP=KAPAA-POOKU-HALII-MAKAPILI SOILS; RM=ROUGH MOUNTAINOUS LAND, ROUGH BROKEN LAND, ROCK OUTCROPS.

area--Inceptisols, Ultisols and Oxisols (Figure 17). Rough, broken land was not classified into any Order.

Group 1.1 and 1.2 correspond with Oxisol areas while Group 2.1 coincide with Ultisol. The small area of Inceptisol make it difficult to relate these soils with any group in the second level grouping. Group 2.2 is rough, broken land according to the SCS soil map.

Third Level Grouping of 108 Cells

In the third level grouping, the 108 cells were segregated into eight groups. This resulted from further subdivision of each group in the second level into two more subgroups. The mean and standard errors of each of the eight groups are shown in Table XXXVII.

A map showing the major soil series in the area was prepared on a transparent overlay and superimposed on the third level grouping (Figure 18). The soil series map printed on the overlay was compiled from the detailed soil series map of the Soil Conservation Service for the same area. There were more than ten series found in that 27-square mile area. However, some series covers only a very small area and it was decided to place these soils as inclusions within the eight major soil series shown in Figure 18.

The comparison between the two maps indicates the lack of correspondence between the third level grouping and the major soil series in the area. Close relationship between the two maps was not really expected because soil series was established mainly on the basis of soil profile characteristics measured in the field and in the laboratory. Consequently, landscape features, although not totally ignored, was not considered as one of the characteristics of the series.

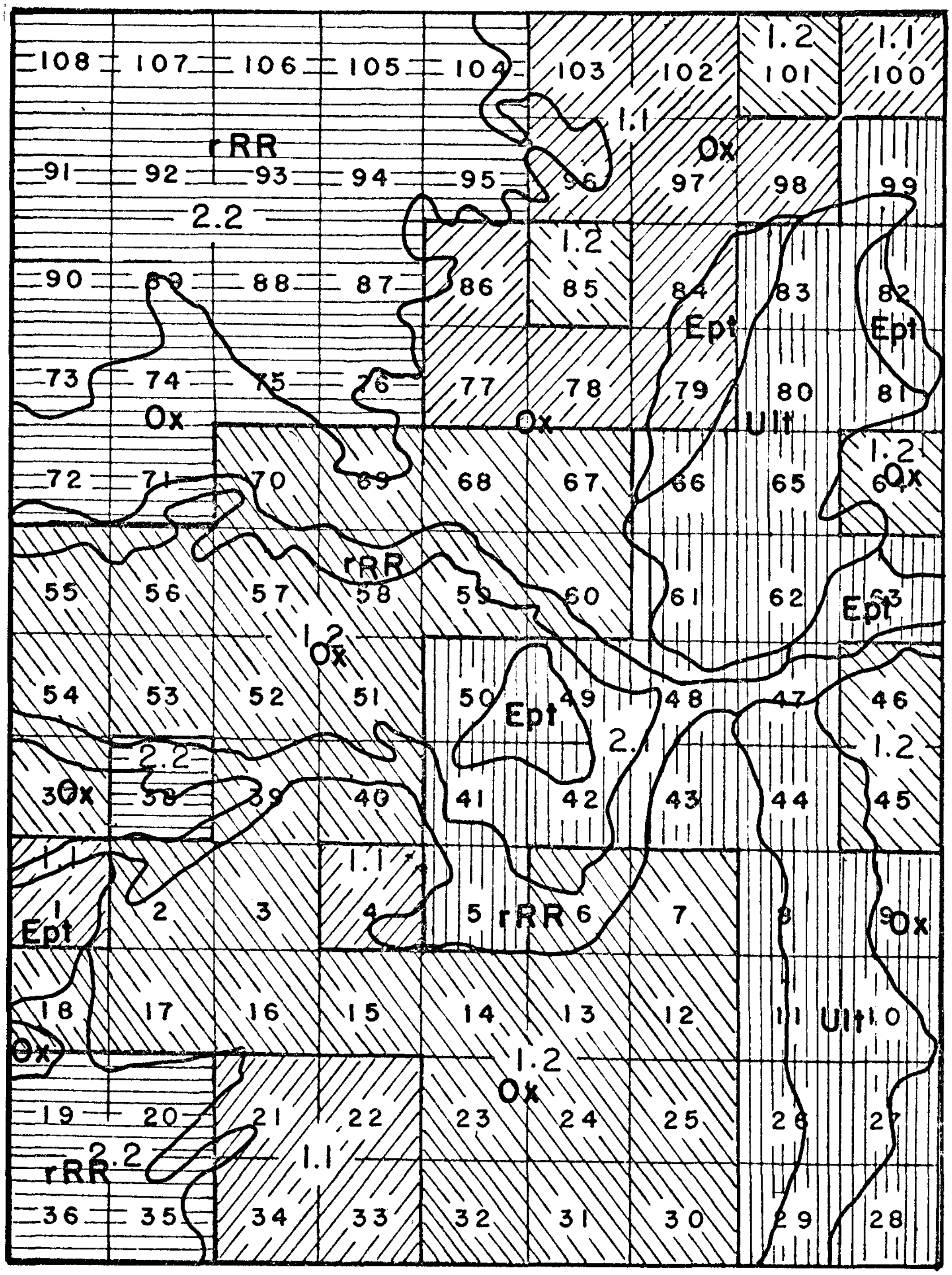


FIG. 17. SECOND LEVEL GROUPING AND SOIL ORDERS (TRANSPARENT OVERLAY) Ept=INCEPTISOL; Ult=ULTISOL, Ox=OXISOL; rRR=ROUGH BROKEN LAND, NOT CLASSIFIED TO ANY SOIL ORDER.

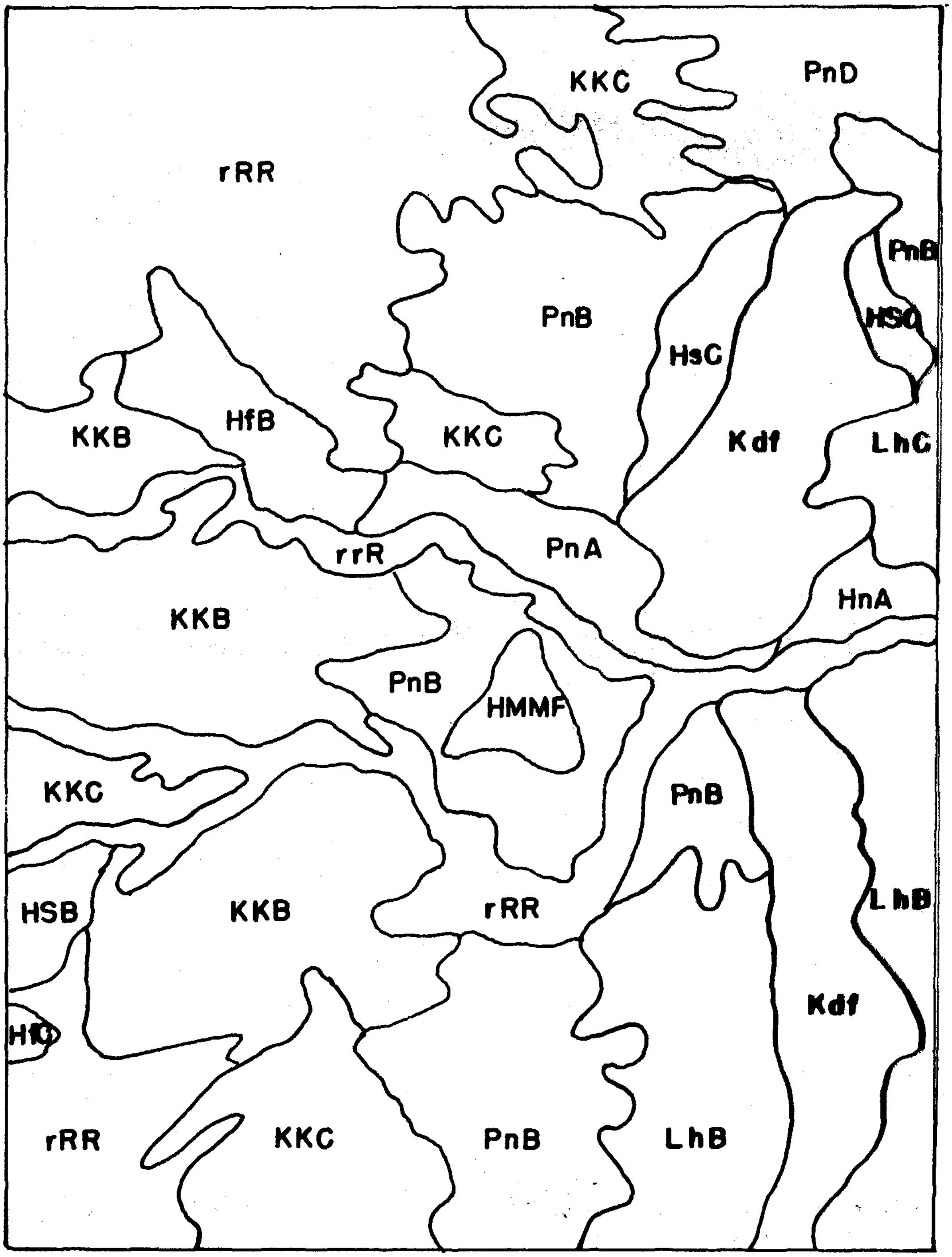

KKC
PnD
rRR
PnB
HsC
PnB
HSC
HfB
KKB
KKC
Kdf
LhC
PnA
rrR
KKB
HnA
PnB
HMMF
KKC
PnB
HSB
KKB
rRR
LhB
Kdf
HfC
rRR
KKC
PnB
LhB

TABLE XXXVII. MEAN AND STANDARD ERROR OF THIRD LEVEL GROUPING OF 108 CELLS ON KAUAI

Terrain Factor	Group 1.11		Group 1.12		Group 1.21		Group 1.22	
	Mean	Standard Error	Mean	Standard Error	Mean	Standard Error	Mean	Standard Error
Ea	336.20	15.95	361.50	15.66	361.00	15.92	226.20	20.88
RL	147.40	24.46	78.60	14.33	88.90	11.89	224.50	29.74
Sm	17.70	0.81	8.60	1.20	6.60	0.68	23.50	2.59
SL	1302.10	115.60	1526.60	75.00	1685.00	92.75	1668.00	106.96
TL	3.82	0.28	3.28	0.11	1.92	0.11	2.15	0.22
Number of cell	8		9		29		10	

Terrain Factor	Group 2.11		Group 2.12		Group 2.21		Group 2.22	
	Mean	Standard Error	Mean	Standard Error	Mean	Standard Error	Mean	Standard Error
Ea	274.10	26.09	526.10	39.88	470.00	17.80	615.10	36.32
RL	439.00	49.35	569.10	54.33	157.10	18.56	230.40	25.23
Sm	24.40	2.68	25.40	2.86	26.50	1.23	23.90	2.33
SL	660.00	51.93	761.60	90.75	884.80	68.93	650.60	46.46
TL	2.88	0.16	2.60	0.24	4.33	0.23	4.17	0.18
Number of cell	15		12		7		8	

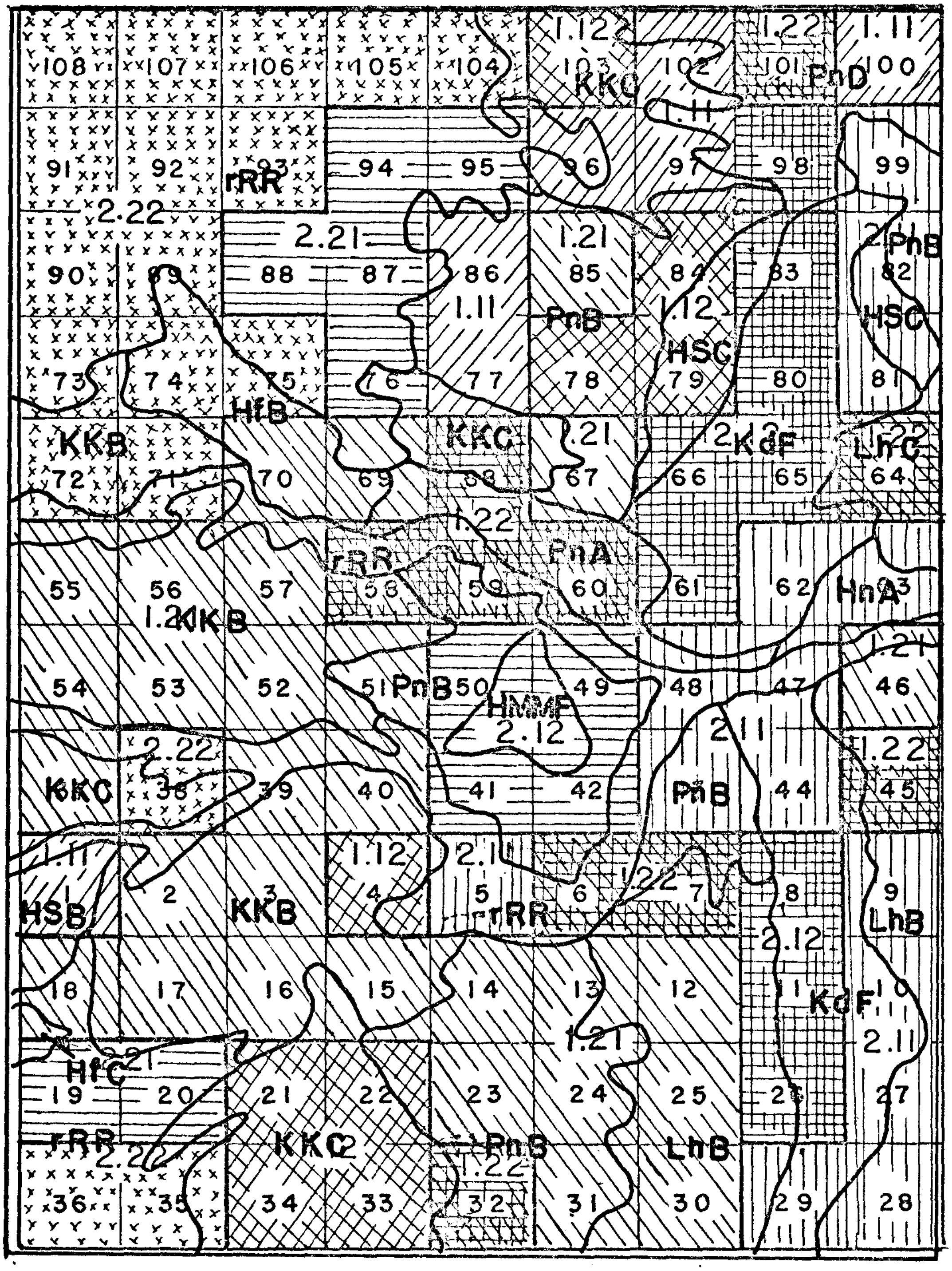
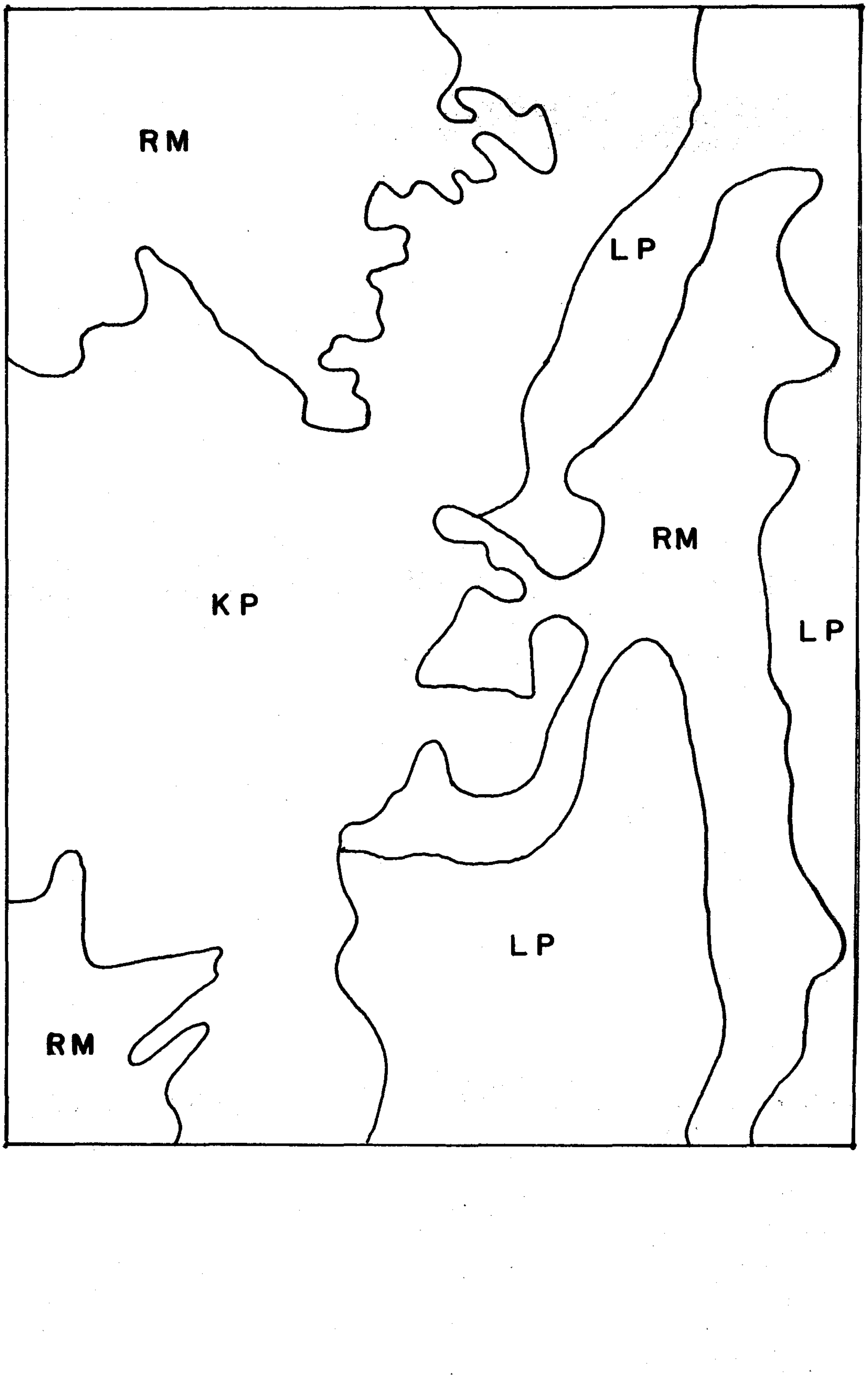


FIG. 18. THIRD LEVEL GROUPING AND MAJOR SOIL SERIES (LATTER ON TRANSPARENT OVERLAY) HfB=HALII GRAVELLY SILTY CLAY (3-8% SLOPE); HnA=HANALEI SOIL (0-3% SLOPE); HMMF= HIHIMANU SILTY CLAY (40-60% SLOPE); LhB=LIHUE SOIL (3-8% SLOPE); Pn=PUHI SOIL; HsB=HANAMAULU SOIL (3-8% SLOPE); Kdf=KALAPA SOIL (40-60% SLOPE); KKB=KAPAA SOIL (3-8% SLOPE); rRR=ROUGH BROKEN LAND.


RM
LP
RM
KP
LP
LP
RM

Because the numerical classification were not designed to separate soils according to the criteria used in mapping soil series, it would be unreasonable to expect a close correspondence between the numerical groupings on the basis of terrain factors and the soil series mapped in the area.

CONCLUSION

This study showed that several terrain factors can be quantified from data easily measured either on topographic maps or aerial photographs or both. The results showed that certain great soil group areas on Oahu and certain soil association areas on Kauai can be differentiated by their quantitative terrain factors. Within the areas of study, terrain form factors such as average elevation, local relief, average slope and slope length were most effective. Stream-associated terrain factors such as land texture ratio and drainage density were also found effective in differentiating some great soil groups on Oahu and soil associations on Kauai.

Both slope length curvature and slope width curvature were found not effective in differentiating soil areas on Oahu and Kauai. Average elevation was another terrain factor not effective in distinguishing between two great soil group areas on Oahu. Lastly, ruggedness number was not effective on Kauai.

The discriminant function equation developed for Tropohumult (Ultisol) and Gibbsihumox (Oxisol) based on average elevation, average slope, slope length and drainage density has satisfactorily segregated the two soil areas on Oahu. However, the equation cannot be used for the associations on Kauai to differentiate the Tropohumults and Gibbsihumoxs. Separate coefficients should be calculated for the four terrain factors on Kauai.

Four terrain factors have been found effective in separating the Haplustox, Eutrorthox and Gibbsihumox areas on Oahu. These factors, in the order of decreasing effectiveness, were average slope, drainage density, slope length and local relief.

A reasonable test of the utility of a classification is whether or not it serves the purpose for which it was intended. The purpose of the numerical groupings was to group the areas of similar terrain factors and to compare with the SCS, USDA, soil map produced for the same area. Based on the comparison made, the numerical classification of cells established in one-half mile grid in eastern Kauai did accomplish this but only when mapping was done on the basis of soil association or soil Order and not when soil series is used. The result of the numerical groupings of cells indicated that numerical methods on the basis of several terrain factors has much to offer in reconnaissance soil surveys of large, relatively undeveloped regions where information about the soil is not available and what is wanted is to predict soil and terrain or land conditions over large areas.

APPLICATION

Many people have pointed out and discussed in many publications the need for expanding the agricultural production of the less developed countries. Along with this concern is the realization that expansion and development of agriculture require information for planning and implementing the projects. For many countries, information about land resources is sparse or may even be absent. The advanced countries have generalized or schematic soil maps for planning and the extension of agricultural knowledge (Kellogg, 1962). The types of soil are fairly well known and detailed soil maps for operational planning are available for most parts of the country. The less developed countries have very few soil maps even for general planning and almost no soil map which can be utilized for operational planning. In fact, as Kellogg (1962) pointed out, millions of farmers in the world are using soils that have never been scientifically examined.

There is tremendous pressure in most of the less developed nations to get the development started even though adequate background information is not available. They have a constant desire for immediate action to push ahead the development schemes, for political or sociological reasons, inspite this lack of information. Of course, it will not be desirable or always possible to avoid this but there are already many examples in the world where agricultural programs have failed because of inadequate knowledge about land resources.

Shortage of manpower and financial support has been the most important reason for very slow pace in soil mapping in all underdeveloped and most of the developing countries. A speedy way of undertaking reconnaissance soil surveys has always been the objective of these countries since they realize that soil is a basic necessity for the success of their agricultural development program. A method which can be used to predict soil and terrain or land conditions over large areas of relatively undeveloped regions is wanted, that is, to be able to make predictions about large areas from minimum amount of soil data. Results presented in this paper suggest that quantitative terrain factor approach has much to offer in reconnaissance soil surveys of large, relatively undeveloped regions.

The world cover of soil maps is quite inadequate. Topographic map is widely available in many underdeveloped countries and many has good aerial photograph coverage. Thus a method for predicting soil based on terrain factors can be done with few trained personnels and minimum amount of capital. How to classify the landscape often has been a problem to soil surveyors. The geomorphological genetic classification is simple in certain types of landscapes such as the depositional landscapes of alluvial or aeolian origin. But in many erosional landscapes geomorphological genetic classification is not well defined. Furthermore, soil surveyors are not always familiar with current geomorphological thinking. As an alternative, the quantitative approach can be applied in which terrain are grouped according to measurable properties, such as the techniques presented in this paper. Terrain factors can all be measured on topographic maps and/or aerial photographs, expressed in numerical values and then classified.

Usually where external aspects of the soil changes, there are corresponding changes in the internal (profile) aspects. Therefore, delineations of the external aspects will contribute to the purpose of soil mapping, although it should be clearly understood that such delineation does not pretend to register the exact nature of soil differences. Differences relating to internal aspect of the soils can only be studied in the field.

Examination of the soil maps revealed that some soil boundaries have no detectable reflection in the terrain features. This is particularly true of soil differences which are the result of some physiographic process which is no longer active and has been obscured by a second process. However, soil bodies adjust themselves to most recent physiographic phenomena although they retain reflections of the former processes in their internal characteristics. Therefore, the boundaries of most units of soil classification are reflected in the present physiography and it is only at the phase, type or series levels that the boundaries may not be recognized. Results of the study on Kauai revealed that this relationship was weak or absent on the series level. Because of this, the boundaries drawn on the basis of physiography (terrain factors) may contain more than one soil series. Difficulty in separating them arises from the fact that no visual differences can be detected on topographic map or aerial photograph. Differences, however, may be detected only by terrain factor quantifications. If the quantitative terrain factors for the two areas are similar, it may be that the soil series are closely related and in many respects may be similar and therefore can very conveniently be called a soil association. This is the most widely used unit for semi-detailed soil surveys in the less developed countries. It is a very convenient unit, because it often serves as management unit and can be used as a guide in agricultural development planning. Only a minimum amount of field work is necessary in areas where accessibility is not a problem. The soil information obtained from these areas can then be extended to inaccessible parts of the region having similar magnitude of quantitative terrain factors. Predictions about ground conditions, in general, of inaccessible areas are inferred from the known conditions obtained from the accessible areas.

If it is desired to separate the area into individual soil series, additional field work is required. It may very well be that higher level of numerical classification of cells may present logical groupings which may have some relationships with the soil series.

APPENDIX

APPENDIX A. SUMMARY OF STATISTICAL DATA FOR EACH OF THE TEN TERRAIN FACTORS MEASURED ON EIGHT GREAT SOIL GROUP AREAS ON OAHU

a. Average Elevation (feet)

Great Soil Group	Mean	Standard Error	Standard Deviation	Coefficient of Variation
Tropohumult	640.09	44.87	297.67	46.5
Haplustox	575.38	61.18	280.39	48.7
Gibbsihumox	1313.00	109.04	534.18	40.7
Eutrorthox	515.50	55.11	246.49	44.7
Rhodustalf	683.50	84.43	258.23	52.4
Dystrandept	1082.18	79.20	285.57	26.4
Humitropept	965.71	38.22	101.13	10.5
Ustropept	696.66	10.85	26.58	3.8

b. Local Relief (feet)

Tropohumult	378.70	24.63	163.40	43.1
Haplustox	407.85	47.02	215.50	52.8
Gibbsihumox	582.91	49.65	243.27	41.7
Eutrorthox	239.00	36.05	161.24	67.5
Rhodustalf	553.16	52.44	222.51	40.2
Dystrandept	526.61	39.76	143.36	27.2
Humitropept	202.85	19.72	52.19	25.7
Ustropept	153.33	29.96	73.39	47.9

APPENDIX A. (CONTINUED) SUMMARY OF STATISTICAL DATA FOR EACH OF THE TEN TERRAIN FACTORS MEASURED ON EIGHT GREAT SOIL GROUP AREAS ON OAHU

c. Average Slope (percent)

Great Soil Group	Mean	Standard Error	Standard Deviation	Coefficient of Variation
Tropohumult	30.25	1.31	8.72	28.8
Haplustox	33.22	3.58	16.43	49.5
Gibbsihumox	58.15	4.28	21.01	36.1
Eutrorthox	14.31	1.83	8.19	57.3
Rhodustalf	36.97	2.50	10.83	29.3
Dystrandept	33.92	2.72	9.83	29.0
Humitropept	13.62	1.55	4.10	30.1
Ustropept	10.35	1.01	2.49	24.1

d. Slope Length (feet)

Tropohumult	1086.80	56.95	377.79	34.8
Haplustox	964.84	130.26	596.95	61.9
Gibbsihumox	451.48	24.00	117.58	26.0
Eutrorthox	1446.59	146.31	654.34	45.2
Rhodustalf	663.10	47.36	200.94	30.3
Dystrandept	785.42	46.57	167.93	21.4
Humitropept	1269.04	126.60	334.96	26.4
Ustropept	1542.21	149.94	367.27	23.8

APPENDIX A. (CONTINUED) SUMMARY OF STATISTICAL DATA FOR EACH OF THE TEN TERRAIN FACTORS MEASURED ON EIGHT GREAT SOIL GROUP AREAS ON OAHU

e. Slope Length Curvature

Great Soil Group	Mean	Standard Error	Standard Deviation	Coefficient of Variation
Tropohumult	0.82	0.04	0.32	39.0
Haplustox	0.99	0.09	0.44	44.7
Gibbsihumox	1.13	0.10	0.49	43.5
Eutrorthox	0.89	0.07	0.33	37.2
Rhodustalf	0.61	0.08	0.36	60.4
Dystrandept	1.10	0.10	0.36	33.2
Humitropept	1.64	0.26	0.69	42.6
Ustropept	1.03	0.15	0.36	35.5

f. Slope Width Curvature (degree)

Tropohumult	40.71	2.16	14.34	35.2
Haplustox	44.70	4.76	21.83	48.9
Gibbsihumox	30.08	1.47	7.20	23.9
Eutrorthox	48.06	2.50	11.21	23.3
Rhodustalf	39.78	2.13	9.04	22.7
Dystrandept	41.50	2.41	8.69	21.0
Humitropept	43.78	4.88	12.92	29.5
Ustropept	58.50	4.26	10.44	17.8

APPENDIX A. (CONTINUED) SUMMARY OF STATISTICAL DATA FOR EACH OF THE TEN TERRAIN FACTORS MEASURED ON EIGHT GREAT SOIL GROUP AREAS ON OAHU

g. Land Texture Ratio (mile^{-1})

Great Soil Group	Mean	Standard Error	Standard Deviation	Coefficient of Variation
Tropohumult	4.02	0.19	1.25	31.3
Haplustox	3.58	0.37	1.69	47.4
Gibbsihumox	4.98	0.30	1.44	29.8
Eutrorthox	1.80	0.16	0.71	39.8
Rhodustalf	3.54	0.20	0.88	25.0
Dystrandept	2.98	0.18	0.68	22.8
Humitropept	2.78	0.25	0.66	23.9
Ustropept	2.33	0.31	0.77	33.3

h. Drainage Density (mile/square mile)

Tropohumult	13.60	0.60	4.00	29.4
Haplustox	12.87	1.28	5.87	45.6
Gibbsihumox	16.65	0.87	4.26	25.6
Eutrorthox	5.74	0.50	2.27	39.6
Rhodustalf	12.15	0.74	3.15	26.0
Dystrandept	9.72	0.50	1.83	18.9
Humitropept	9.25	0.69	1.83	19.9
Ustropept	8.00	0.90	2.21	27.7

APPENDIX A. (CONTINUED) SUMMARY OF STATISTICAL DATA FOR EACH OF THE TEN TERRAIN FACTORS MEASURED ON EIGHT GREAT SOIL GROUP AREAS ON OAHU

i. Ruggedness Number (feet/mile)

Great Soil Group	Mean	Standard Error	Standard Deviation	Coefficient of Variation
Tropohumult	5643.09	517.10	3429.47	60.8
Haplustox	6051.61	950.02	4353.55	71.9
Gibbsihumox	13234.04	1168.08	5722.44	43.2
Eutrorthox	1533.60	295.59	1321.92	86.2
Rhodustalf	7383.33	766.67	3252.70	44.1
Dystrandept	5177.30	477.97	1723.36	33.3
Humitropept	1818.28	119.07	315.05	17.3
Ustropept	1325.33	376.96	923.37	69.7

j. Gully Depth (feet)

Tropohumult	174.04	9.76	64.79	37.2
Haplustox	246.43	25.83	118.39	48.0
Gibbsihumox	444.74	45.66	223.69	50.3
Eutrorthox	93.87	10.84	48.50	51.7
Rhodustalf	289.47	36.60	138.31	47.8
Dystrandept	201.44	10.78	38.87	19.3
Humitropept	84.51	12.48	33.03	39.1
Ustropept	66.91	6.97	17.08	25.5

APPENDIX B. SUMMARY OF STATISTICAL DATA FOR EACH OF THE TEN TERRAIN FACTORS MEASURED ON SIX SOIL ASSOCIATION AREAS ON KAUAI

a. Average Elevation (feet)

Soil Association	Mean	Standard Error	Standard Deviation	Coefficient of Variation
KP	611.70	40.59	222.33	36.3
LP	299.70	17.57	87.88	29.4
MW	861.97	69.67	412.21	74.8
WK	168.64	21.40	80.07	50.5
MK	2730.95	90.43	606.63	22.2
WA	4115.55	79.80	356.90	8.7

b. Local Relief (feet)

KP	174.00	15.30	83.89	48.2
LP	100.00	11.01	55.07	55.1
MW	578.05	53.73	317.87	55.0
WK	88.85	15.38	57.56	64.8
MK	453.57	20.08	134.74	29.7
WA	265.00	26.19	117.16	44.2

c. Average Slope (percent)

KP	12.29	1.08	5.93	48.2
LP	7.33	0.75	3.79	51.7
MW	31.06	2.38	14.11	45.4
WK	4.50	0.85	3.20	71.2
MK	30.73	1.41	9.51	29.7
WA	36.87	1.92	8.61	23.4

APPENDIX B. (CONTINUED) SUMMARY OF STATISTICAL DATA FOR EACH OF THE TEN TERRAIN FACTORS MEASURED ON SIX SOIL ASSOCIATION AREAS ON KAUAI

d. Slope Length (feet)

Soil Association	Mean	Standard Error	Standard Deviation	Coefficient of Variation
KP	1817.71	63.95	350.30	19.3
LP	2146.98	86.33	431.66	20.1
MW	1718.36	78.47	464.25	27.0
WK	1412.45	63.86	238.94	16.9
MK	704.09	19.38	130.04	18.5
WA	651.39	42.83	191.57	29.4

e. Slope Length Curvature

KP	0.89	0.07	0.42	47.0
LP	0.95	0.14	0.71	74.9
MW	0.94	0.07	0.42	44.5
WK	1.25	0.09	0.34	27.2
MK	1.12	0.12	0.84	75.4
WA	0.99	0.11	0.50	50.5

f. Slope Width Curvature (degree)

KP	49.28	3.08	16.88	34.3
LP	57.84	3.69	18.48	32.0
MW	58.16	2.98	17.63	30.3
WK	66.49	3.91	14.64	22.0
MK	47.68	1.16	7.82	16.4
WA	33.95	1.70	7.60	22.4

APPENDIX B. (CONTINUED) SUMMARY OF STATISTICAL DATA FOR EACH OF THE TEN TERRAIN FACTORS MEASURED ON SIX SOIL ASSOCIATION AREAS ON KAUAI

g. Land Texture Ratio (mile^{-1})

Soil Association	Mean	Standard Error	Standard Deviation	Coefficient of Variation
KP	5.22	0.20	1.12	21.4
LP	4.70	0.42	2.11	45.1
MW	4.88	0.28	1.71	35.0
WK	3.01	0.18	0.69	23.0
MK	6.33	0.20	1.36	21.5
WA	8.09	0.32	1.42	17.7

h. Drainage Density (mile/square mile)

Soil Association	Mean	Standard Error	Standard Deviation	Coefficient of Variation
KP	9.98	0.43	2.38	24.2
LP	9.50	0.93	4.68	49.3
MW	9.08	0.49	2.90	31.9
WK	5.77	0.40	1.52	26.5
MK	13.35	0.36	2.43	18.2
WA	18.31	0.91	4.08	22.3

i. Ruggedness Number (feet/mile)

Soil Association	Mean	Standard Error	Standard Deviation	Coefficient of Variation
KP	1793.24	181.97	996.71	55.6
LP	1077.66	163.33	816.68	75.8
MW	5475.27	654.20	3870.30	70.7
WK	560.73	119.50	447.13	79.7
MK	6231.26	413.02	2770.63	44.5
WA	4669.60	536.69	2399.04	51.1

APPENDIX B. (CONTINUED) SUMMARY OF STATISTICAL DATA FOR EACH OF THE TEN TERRAIN FACTORS MEASURED ON SIX SOIL ASSOCIATION AREAS ON KAUAI

j. Gully Depth (feet)

Soil Association	Mean	Standard Error	Standard Deviation	Coefficient of Variation
KP	105.08	11.75	64.63	61.3
LP	58.65	5.67	28.38	48.4
MW	310.96	26.38	158.09	50.3
WK	39.77	4.90	18.33	46.1
MK	231.58	16.80	112.73	48.7
WA	182.33	14.55	65.08	35.7

APPENDIX C. RESULTS OF ANALYSIS OF VARIANCE OF EIGHT GREAT SOIL GROUPS ON OAHU FOR EACH OF TEN TERRAIN FACTORS

Average Elevation (Ea)

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Soil Group	7	11236710.2936	1605244.3277	14.2573
Error	145	16325658.5430	112590.7486	
Total	152	27562368.8366		

Local Relief (RL)

Soil Group	7	2585870.4192	369410.0599	10.5778
Error	145	5063849.9548	34923.1031	
Total	152	7649720.3739		

Average Slope (Sm)

Soil Group	7	28473.7181	4067.6740	25.2085
Error	145	23396.4443	161.3548	
Total	152	51870.1624		

Slope Length (SL)

Soil Group	7	16324639.8464	2332091.4066	14.0370
Error	145	24090145.3086	166138.9332	
Total	152	40414785.1550		

APPENDIX C. (CONTINUED) RESULTS OF ANALYSIS OF VARIANCE OF EIGHT GREAT SOIL GROUPS ON OAHU FOR EACH OF TEN TERRAIN FACTORS

Slope Length Curvature (Slc)

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Soil Group	7	7.3374	1.0482	6.4443
Error	145	23.5850	0.1627	
Total	152	30.9224		

Slope Width Curvature (Swc)

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Soil Group	7	137.3748	19.6250	13.5041
Error	145	210.7230	1.4533	
Total	152	348.0978		

Land Texture Ratio (TL)

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Soil Group	7	137.3748	19.6250	13.5041
Error	145	210.7230	1.4533	
Total	152	348.0978		

Drainage Density (Dd)

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Soil Group	7	1648.3996	235.4857	15.8685
Error	145	2151.7699	14.8398	
Total	152	3800.1694		

APPENDIX C. (CONTINUED) RESULTS OF ANALYSIS OF VARIANCE OF EIGHT GREAT SOIL GROUPS ON OAHU FOR EACH OF TEN TERRAIN FACTORS

Ruggedness Number (Rn)

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Soil Group	7	1952745337.8996	278963619.6999	21.3846
Error	145	1891536759.8782	13045081.1026	
Total	152	3844282097.7778		

Gully Depth (Gd)

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Soil Group	7	1996491.7588	285213.1084	20.5970
Error	145	2007865.2417	13847.3465	
Total	152	4004357.0005		

APPENDIX D. RESULTS OF ANALYSIS OF VARIANCE OF SIX SOIL ASSOCIATIONS ON KAUAI FOR EACH OF TEN TERRAIN FACTORS

Average Elevation (Ea)

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Soil Association	5	303582968.1325	60716593.6265	379.3058
Error	163	26091889.3468	160072.9708	
Total	168	329674857.4793		

Local Relief (RL)

Soil Association	5	5787619.5051	1157523.9010	39.1830
Error	163	4815264.5778	29541.5005	
Total	168	10602884.0828		

Average Slope (Sm)

Soil Association	5	23155.3725	4631.0745	55.2327
Error	163	13666.9926	83.8466	
Total	168	36822.3651		

Slope Length (SL)

Soil Association	5	55650899.4771	11130179.8954	103.4198
Error	163	17542275.0703	107621.3194	
Total	168	73193174.5473		

APPENDIX D. (CONTINUED) RESULTS OF ANALYSIS OF VARIANCE OF SIX SOIL ASSOCIATIONS ON KAUAI FOR EACH OF TEN TERRAIN FACTORS

Slope Length Curvature (Slc)

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Soil Association	5	2.0346	0.4069	1.0832
Error	163	61.2333	0.3757	
Total	168	63.2679		

Slope Width Curvature (Swc)

Soil Association	5	12672.3376	2534.4675	12.2820
Error	163	33636.0230	206.3560	
Total	168	46308.3606		

Land Texture Ratio (TL)

Soil Association	5	283.0945	56.6189	24.9268
Error	163	370.2392	2.2714	
Total	168	653.3337		

Drainage Density (Dd)

Soil Association	5	1917.3200	383.4640	39.3860
Error	163	1586.9768	9.7361	
Total	168	3504.2968		

APPENDIX D. (CONTINUED) RESULTS OF ANALYSIS OF VARIANCE OF SIX SOIL ASSOCIATIONS ON KAUAI FOR EACH OF TEN TERRAIN FACTORS

Ruggedness Number (Rn)

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Soil Association	5	3743835201.4110	748767040.2105	121.5021
Error	163	1003826645.2001	6158445.6025	
Total	168	4747661846.6111		

Gully Depth (Gd)

Soil Association	5	1531369.2718	306273.8544	30.9679
Error	163	1612075.0862	9890.0312	
Total	168	3143444.3580		

APPENDIX E

AERIAL PHOTO STEREOGRAMS

PLATE 1. AERIAL PHOTO STEREOGRAM SHOWING THE EUTRORTHOX (EO) AND TROPOHUMULT (TH) AREAS. SEVEN TERRAIN FACTORS WERE FOUND EFFECTIVE IN DISTINGUISHING BETWEEN THESE TWO SOIL AREAS (TABLE XIV).


EUTRORTHOX
EUTRORTHOX
TROPOHUMULT

PLATE 2. AERIAL PHOTO STEREOGRAM OF GIBBSIHUMOX AREA. THE AREA IS CHARACTERIZED BY RUGGED TOPOGRAPHY WITH AVERAGE ELEVATION GREATER THAN 1000 FEET AND AVERAGE SLOPE MORE THAN 50 PERCENT. GIBBSIHUMOX AREA CAN BE DISTINGUISHED FROM OTHER GREAT SOIL GROUP AREAS BY MEANS OF ANY OF THE TEN TERRAIN FACTORS (TABLE XIV).

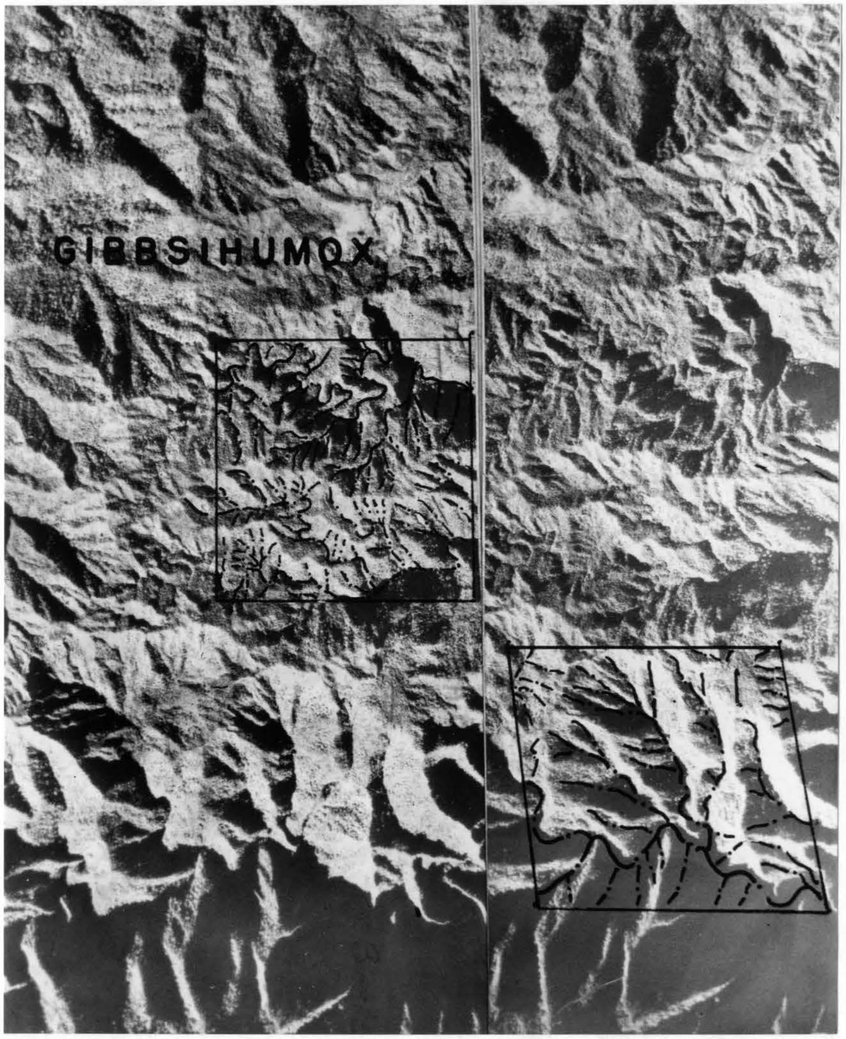

GIBBSIHUMOX

PLATE 3. AERIAL PHOTO STEREOGRAM SHOWING USTROPEPT (UT) AND HUMITROPEPT (HT) AREAS ON OAHU. THESE TWO AREAS HAVE ALMOST SIMILAR MAGNITUDE OF TERRAIN DATA (TABLE XII) AND SEPARATING THEM BY MEAN OF TERRAIN FACTORS WAS VERY DIFFICULT. SLOPE LENGTH CURVATURE WAS THE ONLY TERRAIN FACTOR FOUND EFFECTIVE IN DISTINGUISHING BETWEEN THE TWO AREAS.


E

PLATE 4. UNCULTIVATED PORTION OF HAPLUSTOX AREA. THE AREA CAN BE DISTINGUISHED FROM OTHER GREAT SOIL GROUP AREAS BY USING MANY OF THE TEN TERRAIN FACTORS. HOWEVER, LOCAL RELIEF, AVERAGE SLOPE, DRAINAGE DENSITY AND GULLY DEPTH APPEARED TO BE MORE EFFECTIVE THAN OTHER EXTERNAL FACTORS.

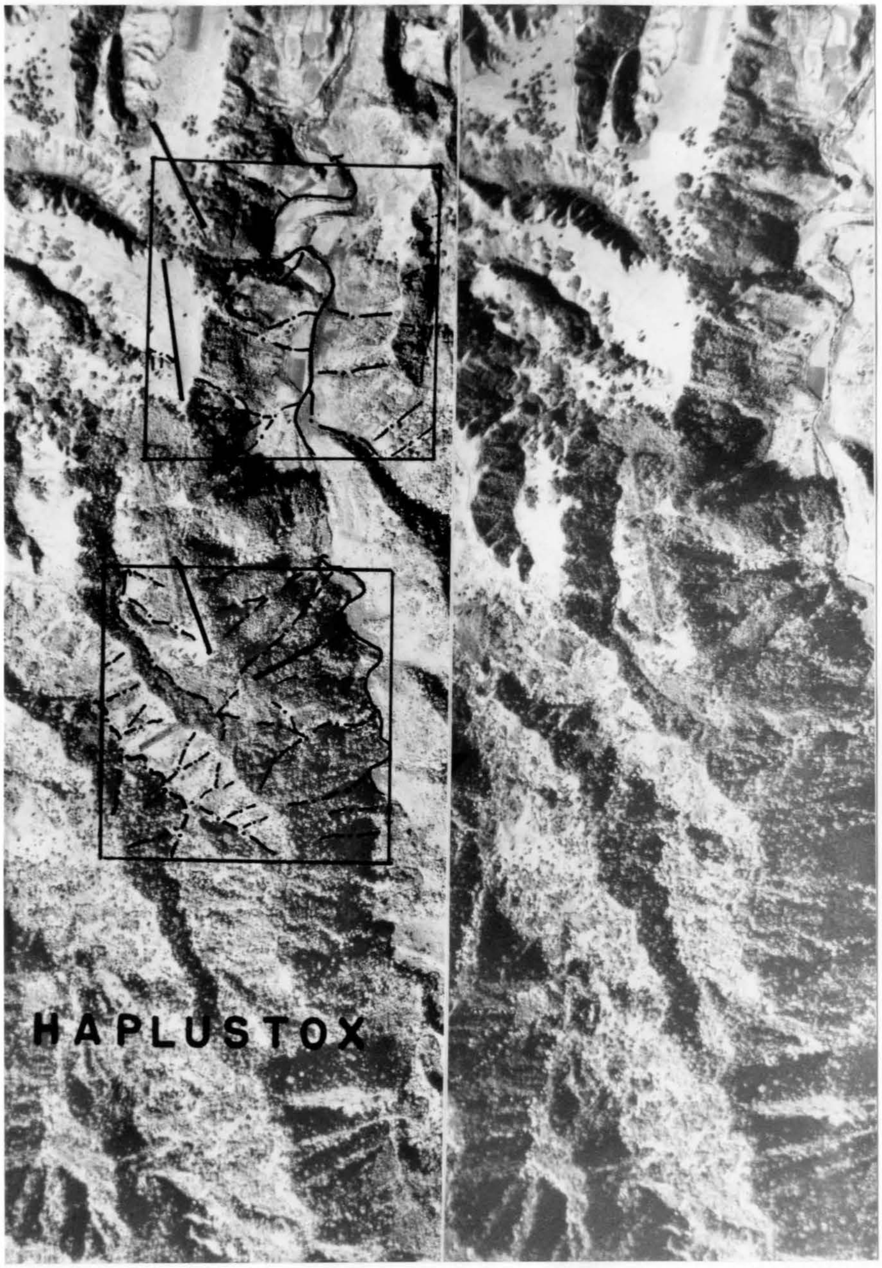

HAPLUSTOX

PLATE 5. AERIAL PHOTO STEREOGRAM OF DYSTRANDEPT AREA. TABLE XII INDICATE THAT AVERAGE ELEVATION, AVERAGE SLOPE AND SLOPE LENGTH WERE EFFECTIVE IN SEPARATING DYSTRANDEPT AREA FROM OTHER GREAT GROUP AREAS CONSIDERED IN THIS PAPER.


DYSTRANDEPT

PLATE 6. AERIAL STEREOGRAM OF RHODUSTALF AREA AND A SMALL PORTION OF CULTIVATED HAPLUSTOX AREA. SLOPE LENGTH AND SLOPE LENGTH CURVATURE APPEARED TO BE EFFECTIVE IN DISTINGUISHING BETWEEN RHODUSTALF AREA AND OTHER GREAT SOIL GROUP AREA IN OAHU.

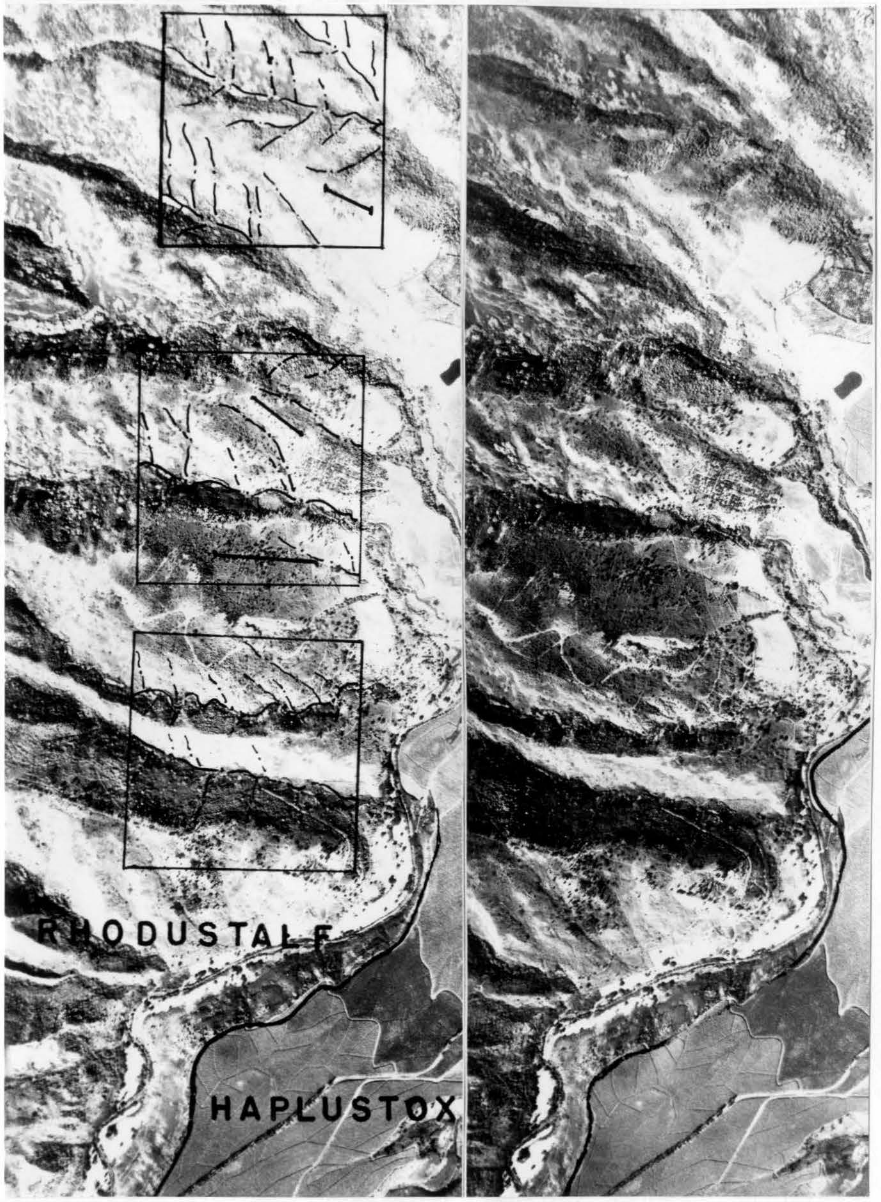
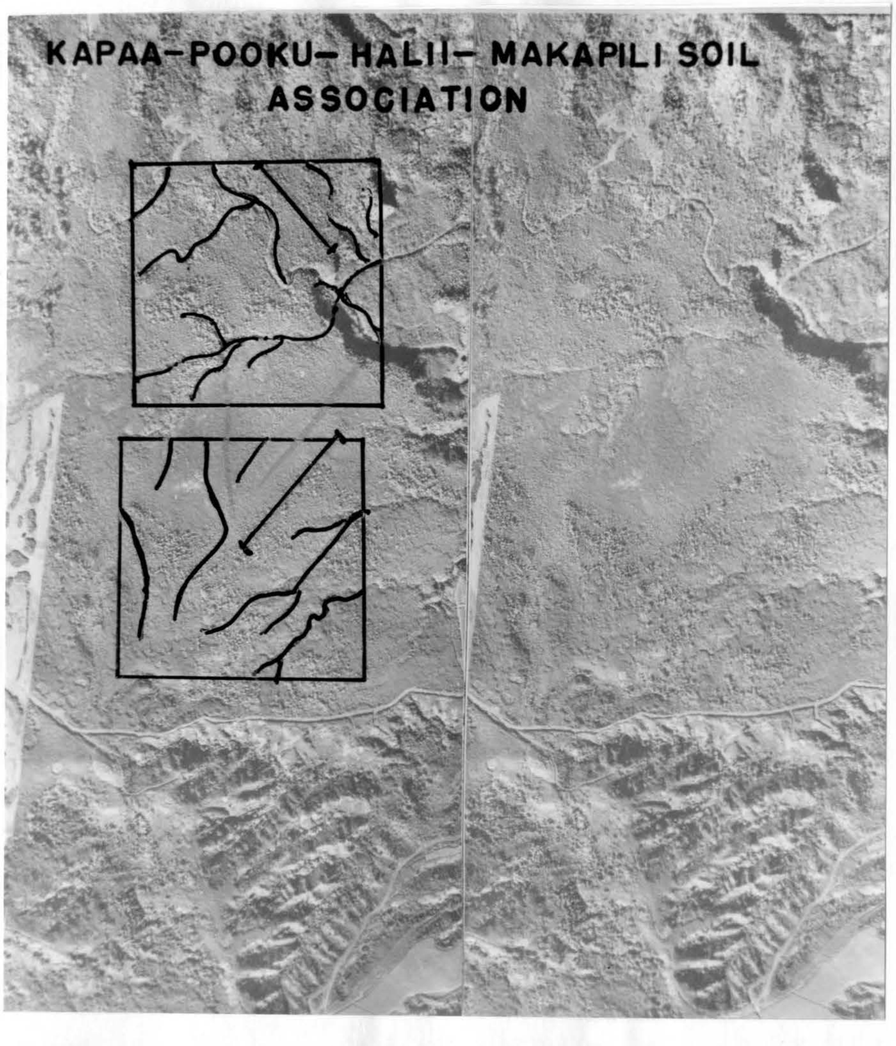

RHODUSTALF
HAPLUSTOX

PLATE 7. AERIAL PHOTO STEREOGRAM OF KAPAA-POOKU-HALII-MAKAPILI SOIL AREA IN EASTERN KAUAI AT ELEVATION RANGING FROM 100 TO 1000 FEET.



KAPAA–POOKU– HALII– MAKAPILI SOIL ASSOCIATION

PLATE 8. AERIAL PHOTO STEREOGRAM OF LIHUE-PUHI SOIL AREA. MOST OF THE SUGAR CANE AND PINEAPPLE IN KAUAI ARE GROWN IN THIS AREA. THE AREA GENERALLY HAVE DEEP, WELL DRAINED, FINE TEXTURED SOIL AND OCCUR PRIMARILY ON EMERGED MARINE PLATFORM ON THE EASTERN COAST OF THE ISLAND.

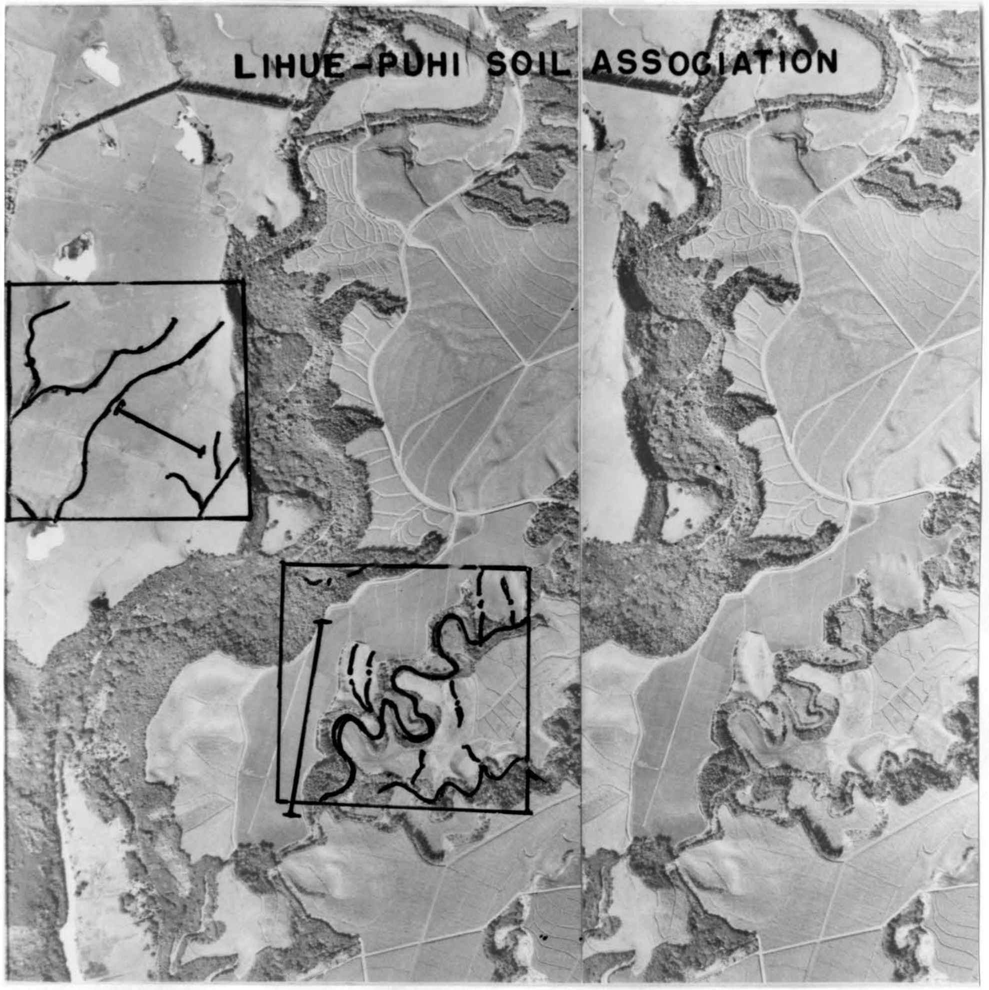

LIHUE-PUHI SOIL ASSOCIATION

PLATE 9. AERIAL PHOTO STEREOGRAM OF WAIKOMA-KALIHI-KOLOA SOIL AREA (WK). THIS SOIL OCCURS ON GENTLY SLOPING UPLANDS (1 TO 8 PERCENT SLOPE) AND NEARLY LEVEL BOTTOMLANDS IN SOUTHERN TIP OF KAUAI. A NUMBER OF TUFF CONES BREAK THE EVENNESS OF THE AREA.

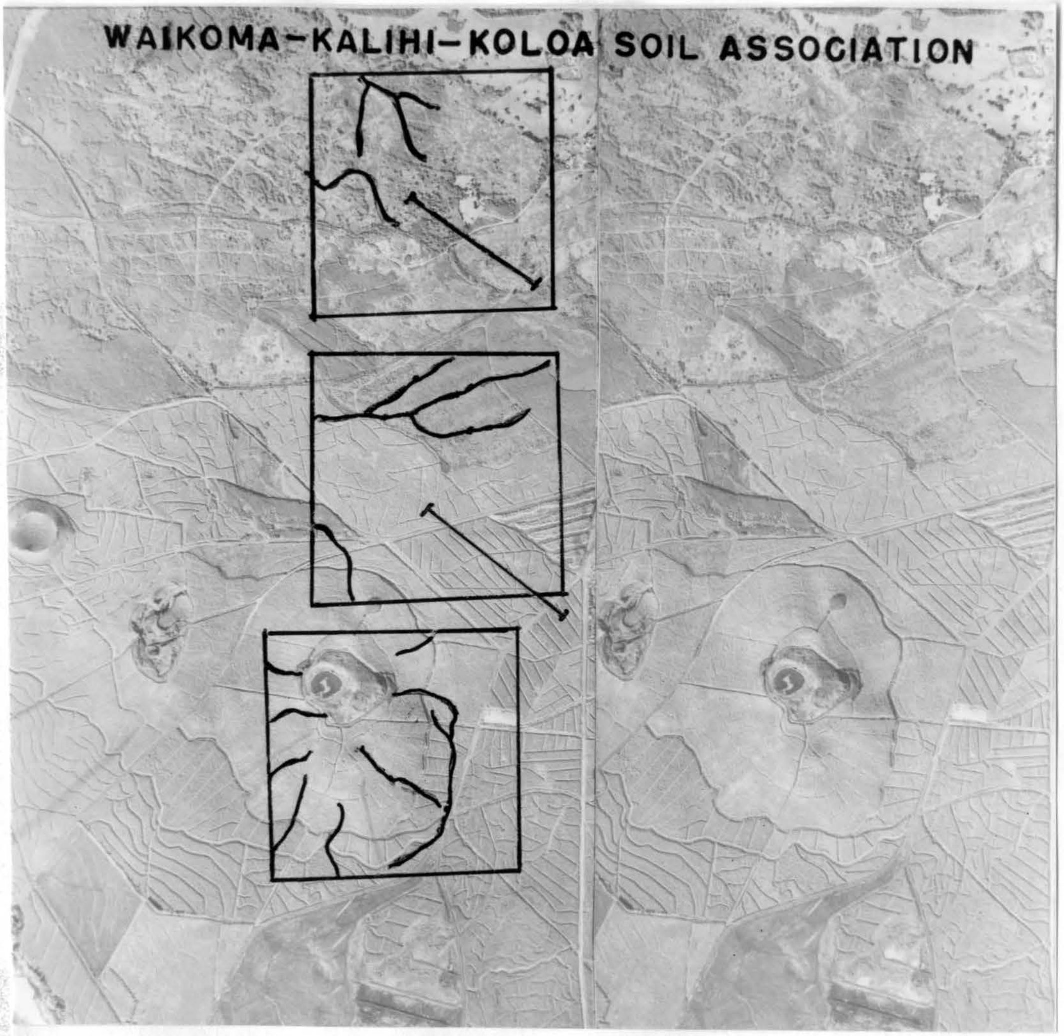

WAIKOMA-KALIHI-KOLOA SOIL ASSOCIATION

PLATE 10. AERIAL PHOTO STEREOGRAM OF MAHANA-KOKEE-PAAIKI SOILS OCCURRING ON WESTERN PART OF KAUAI AT AN AVERAGE ELEVATION OF ABOUT 2700 FEET ABOVE SEA LEVEL. THE AREA IS HIGHLY DISSECTED AND THE MULTIPLICATION OF TRIBUTARIES HAS PRODUCED MORE HIGHLY COMPLICATED DRAINAGE PATTERNS AND FINER TEXTURE TOPOGRAPHY (TABLE XXIII).

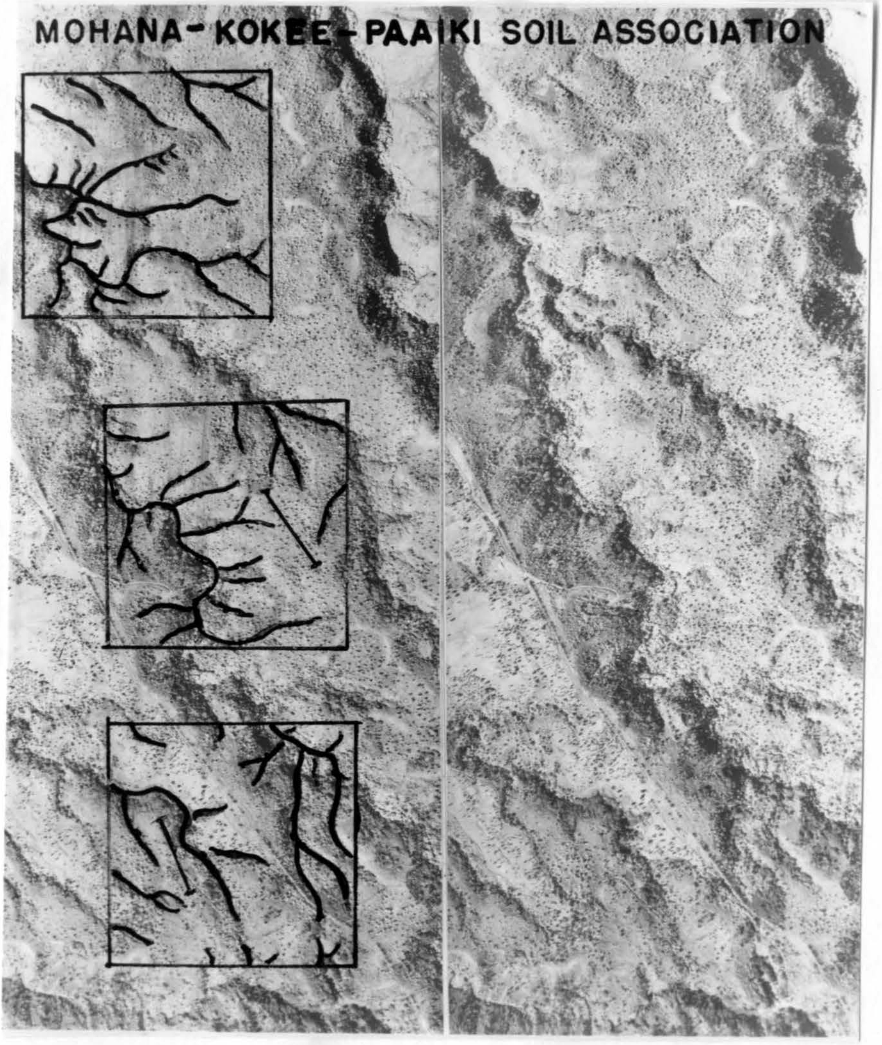

MOHANA-KOKEE-PAAIKI SOIL ASSOCIATION

PLATE 11. AERIAL PHOTO STEREOGRAM OF A PORTION OF WAIALEALE-ALAKAI SOIL AREA (WA). RAINFALL IS HIGH IN THE AREA AND SINCE THE LOCAL RELIEF IS LOW (TABLE XXIII), DRAINAGE IS SLOW AND LARGE AREAS ARE SWAMPY. LOW RIDGES ABOVE THE GENERAL SURFACE ARE BETTER DRAINED.

See Fig 7 on p. 66

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